ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

PRODUCTION NOTE

University of Illinois at
Urbana-Champaign Library
Large-scale Digitization Project, 2007.

UNIVERSITY OF ILLINOIS
BULLETIN

Vol. 41 October 12, 1943 No. 8

ENGINEERING EXPERIMENT STATION
BULLETIN SERIES No. 344

FATIGUE TESTS OF COMMERCIAL BUTT WELDS IN STRUCTURAL STEEL PLATES

A REPORT OF AN INVESTIGATION

conducted by

THE ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS

in cooperation with

THE PUBLIC ROADS ADMINISTRATION, FEDERAL WORKS AGENCY
THE CHICAGO BRIDGE AND IRON COMPANY
ASSOCIATION OF AMERICAN RAILROADS
THE BUREAU OF SHIPS, NAVY DEPARTMENT

by

WILBUR M. WILSON
WALTER H. BRUCKNER
THOMAS H. McCRACKIN, Jr.
HOWARD C. BEEDE

under the supervision of the

COMMITTEE ON FATIGUE TESTING (STRUCTURAL)

of the

WELDING RESEARCH COMMITTEE, THE ENGINEERING FOUNDATION

sponsored by the

AMERICAN WELDING SOCIETY

and the

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

PRICE: ONE DOLLAR
PUBLISHED BY THE UNIVERSITY OF ILLINOIS
URBANA

[Issued weekly. Entered as second-class matter at the post office at Urbana, Illinois, under the Act of August 24, 1912. Office of Publication, 358 Administration Building, Urbana, Illinois. Acceptance for mailing at the special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized July 31, 1918.]

THE Engineering Experiment Station was established by act of the Board of Trustees of the University of Illinois on December 8, 1903. It is the purpose of the Station to conduct investigations and make studies of importance to the engineering, manufacturing, railway, mining, and other industrial interests of the State.

The management of the Engineering Experiment Station is vested in an Executive Staff composed of the Director and his Assistant, the Heads of the several Departments in the College of Engineering, and the Professor of Chemical Engineering. This Staff is responsible for the establishment of general policies governing the work of the Station, including the approval of material for publication. All members of the teaching staff of the College are encouraged to engage in scientific research, either directly or in coöperation with the Research Corps, composed of full-time research assistants, research graduate assistants, and special investigators.

To render the results of its scientific investigations available to the public, the Engineering Experiment Station publishes and distributes a series of bulletins. Occasionally it publishes circulars of timely interest, presenting information of importance, compiled from various sources which may not readily be accessible to the clientele of the Station, and reprints of articles appearing in the technical press written by members of the staff and others.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University. *Above the title on the cover* is given the number of the Engineering Experiment Station bulletin, circular, or reprint which should be used in referring to these publications.

For copies of publications or for other information address

THE ENGINEERING EXPERIMENT STATION,
UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION
BULLETIN SERIES No. 344

FATIGUE TESTS OF COMMERCIAL BUTT WELDS IN STRUCTURAL STEEL PLATES

A REPORT OF AN INVESTIGATION

conducted by

THE ENGINEERING EXPERIMENT STATION, UNIVERSITY OF ILLINOIS

in cooperation with

THE PUBLIC ROADS ADMINISTRATION, FEDERAL WORKS AGENCY

THE CHICAGO BRIDGE AND IRON COMPANY

ASSOCIATION OF AMERICAN RAILROADS

THE BUREAU OF SHIPS, NAVY DEPARTMENT

by

WILBUR M. WILSON
WALTER H. BRUCKNER
THOMAS H. McCRACKIN, JR.
and
HOWARD C. BEEDE

under the supervision of the

COMMITTEE ON FATIGUE TESTING (STRUCTURAL)

of the

WELDING RESEARCH COUNCIL

of

THE ENGINEERING FOUNDATION

sponsored by the

AMERICAN WELDING SOCIETY

and the

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

PUBLISHED BY THE UNIVERSITY OF ILLINOIS

PRICE: ONE DOLLAR

4000—10-43—25850

UNIVERSITY
OF ILLINOIS
:: PRESS ::

CONTENTS

LIST OF FIGURES

LIST OF TABLES

FATIGUE TESTS OF COMMERCIAL BUTT WELDS IN STRUCTURAL PLATES

I. Introduction

1. *Object and Scope of Investigation.*—A comprehensive series of fatigue tests was made on butt welds in ⅞-in. carbon-steel plates that had been welded in the flat position by a skilled welder using a manually-operated metallic arc and working under expert supervision. These welds were considered to be the optimum that could be expected under the present stage of development in this type of welding. Having obtained a fairly satisfactory knowledge of the fatigue strength of butt welds made under favorable conditions, it seemed desirable to make tests of welds made under commercial conditions. Six series of 15 specimens each, purchased from fabricating shops that have had extensive experience in structural welding, were therefore tested in order that the fatigue strength of these commercial welds might be compared with the fatigue strength of the optimum welds, hereinafter designated as the basic series.* These six series were composed of two groups of three series each, designated as group 1 and group 2. All of the specimens of the basic series and of the commercial series referred to in this paragraph were welded in the flat position with a manually-operated metallic arc and were tested in the as-welded condition.

A third group of tests of commercial welds, designated as group 3, was made to determine the fatigue strength of butt welds in ⅞-in. carbon-steel plates welded in various positions and with various electrodes. Except for these two features, the specimens of group 3 were the same as those of groups 1 and 2 referred to in the previous paragraph.

The specimens of groups 1, 2, and 3 were welded in the shop. The specimens for another group of tests, designated as group 4, were welded in the field. There were two series of 14 specimens each in this group, and each series was welded by a different fabricator.

Tests were made on two additional groups of specimens, one designated as group 5, and the other as group 6. The specimens of group 5 were welded by the Unionmelt process and those of group 6 were welded by the Carbon Arc process, both processes being automatic.

The dimensions of the specimens were the same for all series. The plates for groups 2 to 6, inclusive, were from the same heat; the plates for the basic series and for group 1 were from different heats but the composition of the steel was similar for all series.

*Univ. of Ill. Eng. Exp. Sta. Bulletin No. 327.

The fatigue strength of a member, as the term is used in this bulletin, is the maximum stress in a stress cycle that will cause failure at a definite stated number of cycles when the ratio of the minimum to the maximum stress in the cycle has a definite stated value. Two ranges of minimum to maximum stress were used in this investigation:

(1) from a given tensile stress to an equal compressive stress;

(2) from zero to some given tensile stress.

Values of the fatigue strength corresponding to failure at 100 000 cycles and 2 000 000 cycles were determined.

2. *Acknowledgments.*—The tests described in this bulletin are a part of the investigation resulting from a cooperative agreement entered into by the Engineering Experiment Station of the University of Illinois, of which DEAN M. L. ENGER is the Director, and the Public Roads Administration, Federal Works Agency, of which THOMAS H. MACDONALD is Commissioner. The tests were planned in cooperation with the Committee on Fatigue Testing (Structural) of the Welding Research Council of the Engineering Foundation, of which JONATHAN JONES is Chairman. The tests were financed by the Chicago Bridge and Iron Company; the Public Roads Administration, Federal Works Agency; the Bureau of Ships, Navy Department; and the Association of American Railroads. The Carnegie-Illinois Steel Corporation, the Bethlehem Steel Company, Lukenweld, Inc., the Bureau of Ships, the G. E. X-Ray Corporation, the Chicago Bridge and Iron Company, the Lincoln Electric Company, the Lasker Boiler and Engineering Corporation, the Aetna Iron and Steel Company, and the Union Carbide and Carbon Research Laboratories, Inc., contributed materials and services. The fatigue tests were made in the Arthur Newell Talbot Laboratory, and the metallurgical studies were made in the Metallurgical Laboratory, both of the University of Illinois.

The members of the Committee on Fatigue Testing were:

JONATHAN JONES, Chairman, Chief Engineer, Fabricated Steel Construction, Bethlehem Steel Company, Bethlehem, Pa.

RAYMOND ARCHIBALD, Principal Structural Engineer, Public Roads Administration, Federal Works Agency, Washington, D. C.

J. E. BERNHARDT, Bridge Engineer, Chicago and Eastern Illinois Railway, Chicago, Ill.

LEON C. BIBBER, Welding Engineer, Carnegie-Illinois Steel Corporation, Carnegie Building, Pittsburgh, Pa.

H. C. BOARDMAN, Research Engineer, Chicago Bridge and Iron Company, Chicago, Ill.

W. H. BRUCKNER, Research Assistant Professor of Metallurgical Engineering, University of Illinois, Urbana, Ill.

A. W. Carpenter, Engineer of Bridges, New York Central Railroad System, New York City, N. Y.

Everett Chapman, President, Lukenweld, Inc., Coatesville, Pa.

F. H. Frankland, Director of Engineering, American Institute of Steel Construction, Inc., New York City, N. Y.

C. F. Goodrich, Chief Engineer, American Bridge Company, Frick Building, Pittsburgh, Pa.

LaMotte Grover, Structural Welding Engineer, Air Reduction Sales Company, Lincoln Building, New York City, N. Y.

O. L. Grover, Principal Highway Bridge Engineer, Public Roads Administration, Federal Works Agency, Washington, D. C.

W. C. Hopkins, Bridge Engineer, Maryland State Roads Commission, Baltimore, Md.

J. B. Hunley, Engineer of Structures, New York Central Railroad, LaSalle Street Station, Chicago, Ill.

G. F. Jenks, Taylor-Winfield Corporation, Warren, Ohio.

C. H. Jennings, Chemistry and Metallurgical Departments, Westinghouse Electric & Manufacturing Co., Research Laboratories, East Pittsburgh, Pa.

E. F. Kelley, Chief, Division of Tests, Public Roads Administration, Federal Works Agency, Washington, D. C.

A. B. Kinzel, Chief Metallurgist, Union Carbide and Carbon Research Laboratories, Inc., New York City, N. Y.

G. M. Magee, Research Engineer, Association of American Railroads, Chicago, Ill.

Leon S. Moisseiff, Consulting Engineer, New York City, N. Y.

N. W. Morgan, Senior Highway Bridge Engineer, Public Roads Administration, Federal Works Agency, Washington, D. C.

Clyde T. Morris, Professor of Civil Engineering, Ohio State University, Columbus, Ohio.

Bureau of Ships, Navy Department, Washington, D. C.

R. E. Spaulding, Consulting Engineer, Aetna Iron and Steel Company, Jacksonville, Fla.

Wm. Spraragen, Executive Secretary, Welding Research Council, New York City, N. Y.

R. L. Templin, Chief, Engineer of Tests, Aluminum Company of America, Research Laboratories, New Kensington, Pa.

A. R. Wilson, Engineer of Bridges and Buildings, Pennsylvania Railroad, Philadelphia, Pa.

W. M. Wilson, Research Professor of Structural Engineering, Talbot Laboratory, University of Illinois, Urbana, Ill.

II. Specimens Welded in Flat Position
Series X, Y, and Z; Group 1

3. *Description of Specimens.*—Previous to the tests of this group, tests had been made to determine the fatigue strength of butt welds in ⅞-in. carbon-steel plates made under careful supervision.* The results of these tests are considered basic, and are used as a standard with which to compare the fatigue strength of other welds. The object of the present series was to determine the fatigue strength of butt welds in ⅞-in. carbon-steel plates of the quality that might reasonably be expected for commercial work from a first-class fabricating shop. Specimens similar in size, shape, and composition of material to the

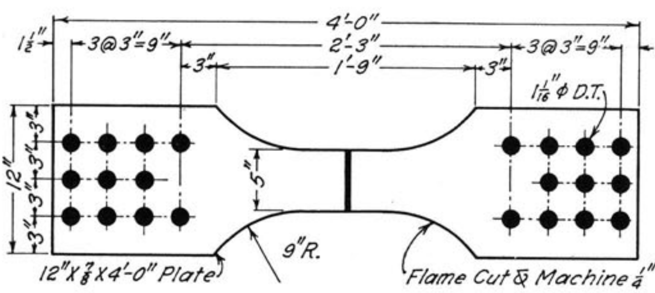


Fig. 1. Details of Specimens for Tests of Butt Welds in ⅞-in. Carbon-Steel Plates

specimens of the basic series were purchased from three well-known fabricators, known as X, Y, and Z, and the fatigue strength of the three groups of specimens was determined and compared with the fatigue strength of the basic series.

The specimens for all series of group 1 were made from ⅞-in. carbon-steel plates and had the dimensions shown in Fig. 1. The fabricators were allowed to follow their usual welding practice, and the procedure followed by each is shown in Fig. 2. The chemical composition of the base metal, determined from samples cut from the specimens, is given in Table 1; and the physical properties of the base metal, as determined by tests of control specimens, are given in Table 2. The location in the parent plate of each fatigue specimen and each control specimen is shown in Fig. 3. Specimens 1 to 15, inclusive, were welded, whereas specimens 16 to 30, inclusive, were plates without welds. A few of the latter of each series were tested to

*Univ. of Ill. Eng. Exp. Sta. Bulletin No. 327.

TABLE 1
CHEMICAL COMPOSITION OF BASE METAL
X, Y, and Z Series

Specimens	Chemical Composition				
	C	Mn	Si	P	S
X	0.249	0.494	0.001	0.009	0.029
Y	0.236	0.466	0.031	0.017	0.029
Z	0.192	0.510	0.008	0.018	0.029

determine whether or not there was any inherent fatigue weakness in the plates that might account for a low fatigue strength of the welded joint. None was found.

The specimens were purchased from the fabricators. Although the contract called for the welding to be done in accordance with the

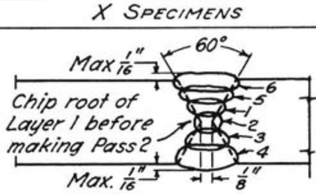
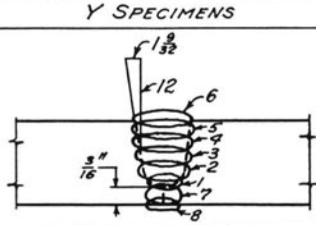
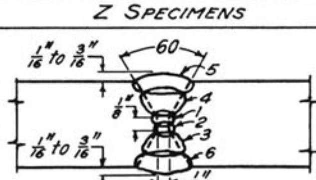
Electrode	Weld Section	Pass No.	Elect. Size	Welding Current, Amperes
X SPECIMENS				
A.W.S E-6012		All	3/16"	200-225
Y SPECIMENS				
A.W.S. E-6030		1 2,3,4,5,7 6,8	3/16" 1/4" 1/4"	250 330 330
Z SPECIMENS				
A.W.S. E-6010		1,2 3,4 5,6	5/32" 5/32" 1/4"	140 175 275

FIG. 2. DETAILS OF WELDS. X, Y, AND Z SPECIMENS

TABLE 2
PHYSICAL PROPERTIES OF BASE METAL
X, Y, and Z Series

Specimen No.	Strength, lb. per sq. in.		Elongation in 8 Inches, per cent	Reduction of Area, per cent
	Yield Point*	Ultimate		
X Series				
X1	30 900	58 700	31.2	54.5
X2	30 200	58 100	33.4	56.1
X3	30 000	58 200	31.6	56.6
X4	30 300	58 300	29.4	55.0
X5	30 800	58 700	29.2	58.8
X6	30 500	58 600	30.2	56.5
X7	30 700	59 000	32.1	55.4
X8	30 900	59 400	30.9	52.0
X9	31 200	60 000	29.0	48.7
X10	31 500	60 600	25.7	42.5
	Av. 30 700	58 960	30.3	53.6
Y Series				
Y1	29 400	62 300	29.0	53.0
Y2	30 000	62 500	28.1	52.6
Y3	29 100	61 800	29.0	53.0
Y4	29 800	62 500	29.6	52.9
Y5	29 800	62 000	28.3	51.2
Y6	29 700	62 200	29.0	52.8
Y7	29 600	61 800	29.0	52.0
Y8	29 000	62 300	28.1	52.0
Y9	29 400	62 900	29.5	52.5
Y10	29 400	62 800	28.7	52.2
	Av. 29 500	62 300	28.8	52.4
Z Series				
Z1	31 000	61 000	28.8	60.0
Z2	31 000	61 200	29.6	60.0
Z3	30 600	60 500	30.6	59.7
Z4	30 700	60 500	31.3	60.0
Z5	31 400	60 300	30.3	59.4
Z6	31 800	60 800	28.7	59.5
Z7	31 100	59 600	29.7	59.6
Z8	30 400	59 400	30.5	59.2
Z9	31 000	59 500	30.3	57.4
Z10	31 000	59 500	28.5	57.7
	Av. 31 000	60 230	29.8	59.2

*By drop of beam.

American Welding Society's 1939 Specifications for Welded Highway and Railway Bridges, the work was not inspected by anyone except regular employees of the fabricator.

Some specimens were tested on a cycle in which the stress varied from tension to an equal compression, others were tested on a cycle in which the stress varied from zero to a maximum tension.

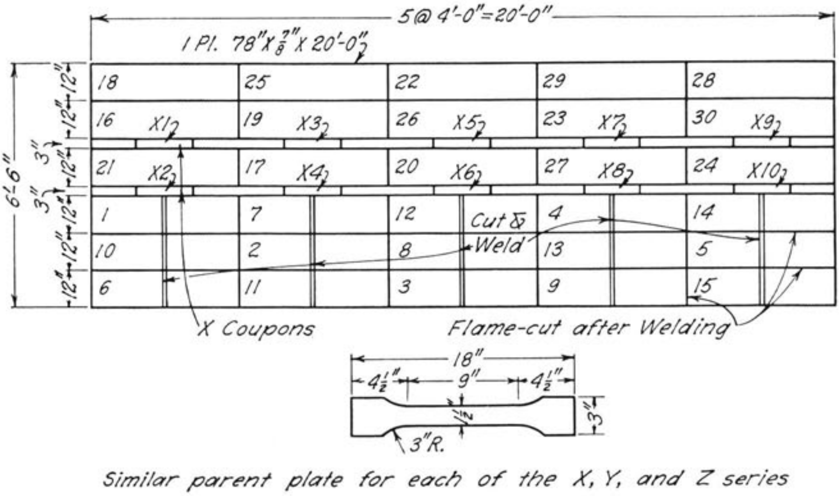


FIG. 3. LOCATION OF SPECIMENS IN PARENT PLATE

To facilitate comparisons, at least three specimens from each fabricator were tested on each of the following cycles: 0 to +30 000, 0 to +25 000, +20 000 to −20 000, and +16 000 to −16 000 lb. per sq. in. The results of the tests are given in Section 4.

4. *Results of Fatigue Tests.*—The results of the individual tests are given in Tables 3, 4, and 5 for series X, Y, and Z, respectively. The corresponding data for the basic series are given in Table 6.* All specimens were tested in the as-welded condition (reinforcement on, not stress relieved).

*This is the same as Table 6 of the University of Illinois Engineering Experiment Station Bulletin No. 327.

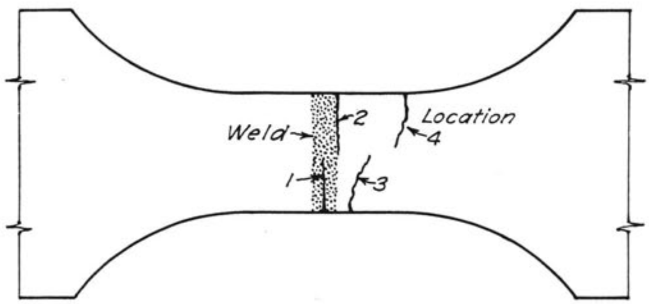


FIG. 4. LOCATION OF FATIGUE CRACKS INDICATED BY NUMBERS IN TABLES

TABLE 3
FATIGUE STRENGTH OF BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION
X Series

Speci-men No.	Cycle	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack*
				Static	Fatigue, F		
					$n =$ 100 000	$n =$ 2 000 000	
X1	0 to Tens.	0 to 30.0	220.7	58.960	33.3		1
X2	0 to Tens.	0 to 30.0	591.2		37.8		2
X3	0 to Tens.	0 to 30.0	202.6		32.9		1
Av.					34.7		
X4							
X5	Comp. Rev.	+20.0 to −20.0	165.7		21.3		1
X6	Comp. Rev.	+20.0 to −20.0	361.6		23.6		1
X7	Comp. Rev.	+20.0 to −20.0	120.5		20.5		4
Av.					21.8		
X8	0 to Tens.	0 to 25.0	488.3			20.8	1
X9	0 to Tens.	0 to 25.0	1060.8			23.0	2
X10	0 to Tens.	0 to 25.0	548.5			21.1	1
X11	0 to Tens.	0 to 25.0	300.0			19.5	1
Av.						21.1	
X12							
X13	Comp. Rev.	+16.0 to −16.0	393.7			13.0	1
X14	Comp. Rev.	+16.0 to −16.0	202.8			11.9	1
X15	Comp. Rev.	+16.0 to −16.0	400.6			13.0	1
Av.						12.6	

*See Fig. 4.

The results of the tests of the X and Z series, and of many of the other commercial series described later, were so erratic that the S-N diagrams could not be determined satisfactorily from these tests alone. Instead, the fatigue strength for failure at 100 000 and 2 000 000 cycles, given in Tables 3, 4, 5, and 6, were computed from the maximum stress in the cycle and the actual number of cycles at failure by the use of the empirical equation,* $F = S\ (N/n)^K$, in which F is the fatigue strength corresponding to failure at n cycles, S is the maximum stress in the stress cycle which caused failure at N cycles, and K is an experimental constant whose value depends upon the stress-raising characteristics of the specimen. The constant K was taken as 0.13 for these tests.

The S-N diagrams for the various series are shown on Fig. 5. The slope of the lines was determined by the value of K (0.13) in the empirical equation, and the position of each line was determined in the following manner:

Referring to Fig. 5, broken lines were drawn upward and to the

*This equation was found to be applicable to the tests of butt welds in ⅞-in. carbon-steel plates with the reinforcement on, given in Bulletin 327.

TABLE 4
FATIGUE STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION
Y Series

Speci-men No.	Cycle	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack*
				Static	Fatigue, F		
					n = 100 000	n = 2 000 000	
Y1	0 to Tens.	0 to 30.0	147.7	62.3	31.6		2
Y2	0 to Tens.	0 to 30.0	132.5		31.1		2
Y3	0 to Tens.	0 to 30.0	228.0		33.4		2
Y12	0 to Tens.	0 to 27.5	217.7		30.4		2
Av.					31.6		
Y5	Comp. Rev.	+20.0 to −20.0	329.9		23.3		2
Y6	Comp. Rev.	+20.0 to −20.0	84.7		19.6		1
Y7	Comp. Rev.	+20.0 to −20.0	184.0		21.7		2
Av.					21.5		
Y9	0 to Tens.	0 to 25.0	678.3			21.7	2
Y10	0 to Tens.	0 to 25.0	631.7			21.5	2
Y11	0 to Tens.	0 to 25.0	603.5			21.4	2
Av.						21.5	
Y8	Comp. Rev.	+16.0 to −16.0	833.5			14.3	2
Y13	Comp. Rev.	+16.0 to −16.0	213.4			12.0	2
Y14	Comp. Rev.	+16.0 to −16.0	1254.2			15.1	2
Y15	Comp. Rev.	+16.0 to −16.0	737.5			14.1	2
Av.						13.9	

*See Fig. 4.

left from the points representing the results of individual tests at high unit stresses. These lines intersect the vertical, $N = 100\ 000$, at points representing the fatigue strength corresponding to failure at 100 000 cycles for the various tests made at a high unit stress. The average of the values represented by these intersecting points is represented by X. Likewise, broken lines were drawn downward and to the right from points representing the results of individual tests at low unit stresses. They intersect the vertical, $N = 2\ 000\ 000$, at points representing the fatigue strength corresponding to failure at 2 000 000 cycles for the various tests made at a low unit stress. The average of the values represented by these intersecting points is represented by Y. The slope of these broken lines is determined by the value of K, 0.13 in this instance. Lines passing through X and Y and having the equation $F = S\ (N/n)^{0.13}$ are the S-N diagram and should coincide. If they do not, either the equation is not strictly applicable or the high-stress and low-stress groups of tests are not consistent with each other. The lowest S-N diagrams of Fig. 5, determined in this manner, represent the experimental data very well. These are for the basic series, one for

TABLE 5
FATIGUE STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION
Z Series

Specimen No.	Cycle	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Strength in 1000's of lb. per sq. in.			Location of Fatigue Crack*
				Static	Fatigue, F		
					$n =$ 100 000	$n =$ 2 000 000	
Z1	0 to Tens.	0 to 30.0	123.0		30.8		1
Z2	0 to Tens.	0 to 30.0	134.5		31.2		1
Z3	0 to Tens.	0 to 30.0	112.8		30.5		1
Av.					30.8		
Z5	Comp. Rev.	+20.0 to −20.0	134.2		20.8		1
Z6	Comp. Rev.	+20.0 to −20.0	42.6		17.9		1
Z7	Comp. Rev.	+20.0 to −20.0	192.7		21.8		1
Av.					20.2		
Z8	0 to Tens.	0 to 25.0	177.8	60.23		18.3	1
Z9	0 to Tens.	0 to 25.0	1052.1			23.0	2
Z10	0 to Tens.	0 to 25.0	2725.2			25.0+	4
Z11	0 to Tens.	0 to 25.0	179.7			18.3	1
Av.						21.2	
Z12	Comp. Rev.	+16.0 to −16.0	597.6			13.7	1
Z13	Comp. Rev.	+16.0 to −16.0	1634.3			15.6	1
Z14	Comp. Rev.	+16.0 to −16.0	244.2			12.3	2
Z15	Comp. Rev.	+16.0 to −16.0	56.2			10.5	1
Av.						13.0	

*See Fig. 4.

which the tests were quite consistent. The S-N diagrams of Figs. 5(a) and 5(c) do not represent the data satisfactorily in all instances for the simple reason that the results of the tests are so inconsistent that no diagram can represent them satisfactorily. Specimens that were intended to be identical had greatly differing fatigue strengths, as illustrated by the following tests reported in Table 3. Specimen X11 failed after 300 000 cycles in which the stress varied from zero to 25 000 lb. per sq. in., whereas X9 withstood 1 060 800 repetitions of the same cycle, and X2 withstood 591 200 cycles in which the stress varied from zero to 30 000 lb. per sq. in. Likewise, Table 5 contains the results of the following inconsistent tests. Specimens Z13 and Z15 were both tested on a cycle in which the stress varied from 16 000 lb. per sq. in. tension to an equal compression. The former withstood 1 634 300 cycles, whereas the latter failed at 56 200 cycles. Specimens Z8, Z9, Z10, and Z11 were all tested on a cycle in which the stress varied from zero to 25 000 lb. per sq. in. tension. The numbers of cycles at failure for the four were 177 800, 1 052 100, 2 725 200, and 179 700,

TABLE 6
FATIGUE STRENGTH OF BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION
Basic Series

Specimen No.	Plate No.	Cycle	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Strength in 1000's of lb. per sq. in.: Static	Fatigue, F: n = 100 000	Fatigue, F: n = 2 000 000	Location of Fatigue Crack*
C1	1	Complete reversal	+20.0 to −20.0	167.9	63.8	21.4		2, 3
C2	1		+20.0 to −20.0	251.9		22.6		2, 3
C3	1		+20.0 to −20.0	271.5		22.8		2
					Av.	22.3		
C4	1		+16.0 to −16.0	753.6			14.1	2, 3
D1	2		+16.0 to −16.0	1795.8	58.2		15.8	2
D2	2		+16.0 to −16.0	947.2			14.5	4
D3	2		+16.0 to −16.0	473.6			13.3	2
					Av.		14.4	
K1	1	0 to tension	0 to 30.0	253.2	63.1	33.9		2
K2	1		0 to 30.0	241.7		33.7		1, 2
K3	1		0 to 30.0	190.9		32.6		1, 2
K4	1		0 to 28.0	277.1		32.0		2
					Av.	33.1		
L1	2		0 to 25.0	1114.4	58.2		23.2	2
L2	2		0 to 25.0	763.4			22.1	2
L3	2		0 to 25.0	816.0			22.3	2
					Av.		22.5	
S1	1	Tension to ½ tension	+22.0 to +44.0	442.0	63.2	53.4		2
S2	1		+22.0 to +44.0	485.0		54.0		2
S3	1		+22.0 to +44.0	388.0		52.5		2
					Av.	53.3		
S4	1		+19.0 to +38.0	1180.7			35.5	2
T1	2		+19.0 to +38.0	2314.2	58.2		38.0+	2
T2	2		+19.0 to +38.0	2471.1			38.0+	2
T3	2		+19.0 to +38.0	1421.6			36.4	2
					Av.		36.9	

*See Fig. 4.

respectively. The results were somewhat more consistent for the Y than for the X and Z series but there were two low values for the Y series. Specimens Y5 and Y6 were both tested on a cycle in which the stress varied from 20 000 lb. per sq. in. tension to an equal compression. The numbers of cycles at failure for the two were 329 900 and 84 700, respectively. Specimens Y13 and Y14 were both tested on a cycle in which the stress varied from 16 000 lb. per sq. in. tension to an equal compression. The numbers of cycles at failure for the two were 213 400 and 1 254 200, respectively. In considering these data, the fact should be realized that a large difference in the number of cycles for failure corresponds to a relatively small difference in the fatigue strength.

A summary of the results of the fatigue tests is given in Table 7. The left-hand portion gives the fatigue strength for failure at 100 000

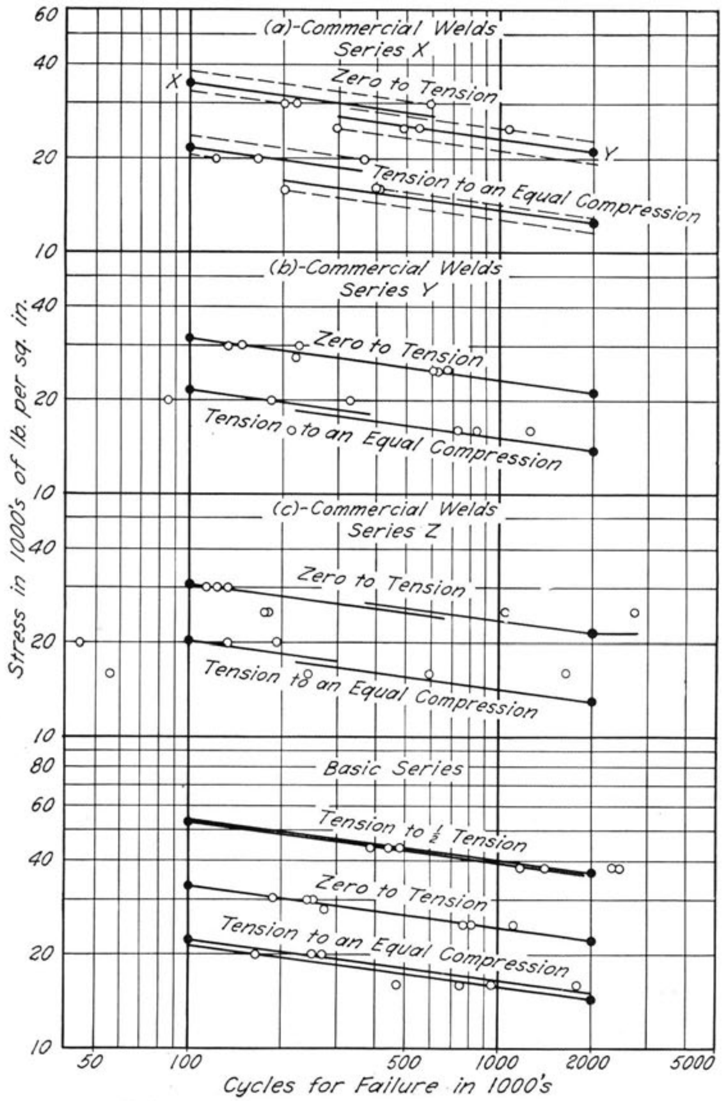


FIG. 5. S–N DIAGRAMS FOR COMMERCIAL BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES. X, Y, Z, AND BASIC SERIES

TABLE 7

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION

X, Y, and Z Series; Summary of Results

Stress Cycle	Fatigue Strength, lb. per sq. in. n = 100 000				Fatigue Strength, lb. per sq. in. n = 2 000 000			
	Basic Series	X Series	Y Series	Z Series	Basic Series	X Series	Y Series	Z Series
Average Values								
Zero to tension	33 100 1.00	34 700 1.05	31 600 0.95	30 800 0.93	22 500 1.00	21 100 0.94	21 500 0.96	21 200 0.94
Tension to equal compression	22 300 1.00	21 800 0.98	21 500 0.96	20 200 0.91	14 400 1.00	12 600 0.88	13 900 0.97	13 000 0.90
Minimum Values								
Zero to tension	32 000 0.97	32 900 0.99	30 400 0.92	30 500 0.92	22 100 0.98	19 500 0.87	21 400 0.95	18 300 0.81
Tension to equal compression	21 400 0.96	20 500 0.92	19 600 0.88	17 900 0.80	13 300 0.92	11 900 0.83	12 000 0.83	10 500 0.73

The upper of the two lines gives the fatigue strength in lb. per sq. in.; for the upper part of the table, the lower lines give the *ratio of average values;* for the lower part of the table, the lower lines give the *ratio of minimum-to-average values.*

Each value is the average of either three or four tests and each minimum is the minimum of a group of either three or four tests.

cycles and the right-hand portion the fatigue strength for failure at 2 000 000 cycles. The upper part of the table gives the averages for the groups, either three or four tests per group, and the lower part the minimum value for any test of a group. The lower of the two lines of figures gives the *ratio of average values* of fatigue strength,* or the *ratio of minimum-to-average values,* as the case may be. It is of interest to note that the average values for the X, Y, and Z series compare favorably with the average values for the basic series, the lowest *ratios of average values* being 0.88 and 0.90 for the X and Z series for failure at 2 000 000 repetitions of a cycle in which the stress was completely reversed. The minimum values are not, however, so reassuring, the four low *ratios of minimum-to-average values* being 0.73, 0.80, 0.83, and 0.83.

A study was made to determine the cause of the occasional low fatigue strength. The reinforcement projects slightly above the base

*These ratios are used frequently in discussing the results of the tests, and the following terminology has been used for convenience in reference: Here and elsewhere, the term "ratio of average values" has been used to designate the ratio of the average fatigue strength for a group of any series to the average fatigue strength of the corresponding group of the basic series; and the term "ratio of minimum-to-average values" has been used to designate the ratio of the minimum fatigue strength for any specimen of a group of any series to the average fatigue strength of the corresponding group of the basic series.

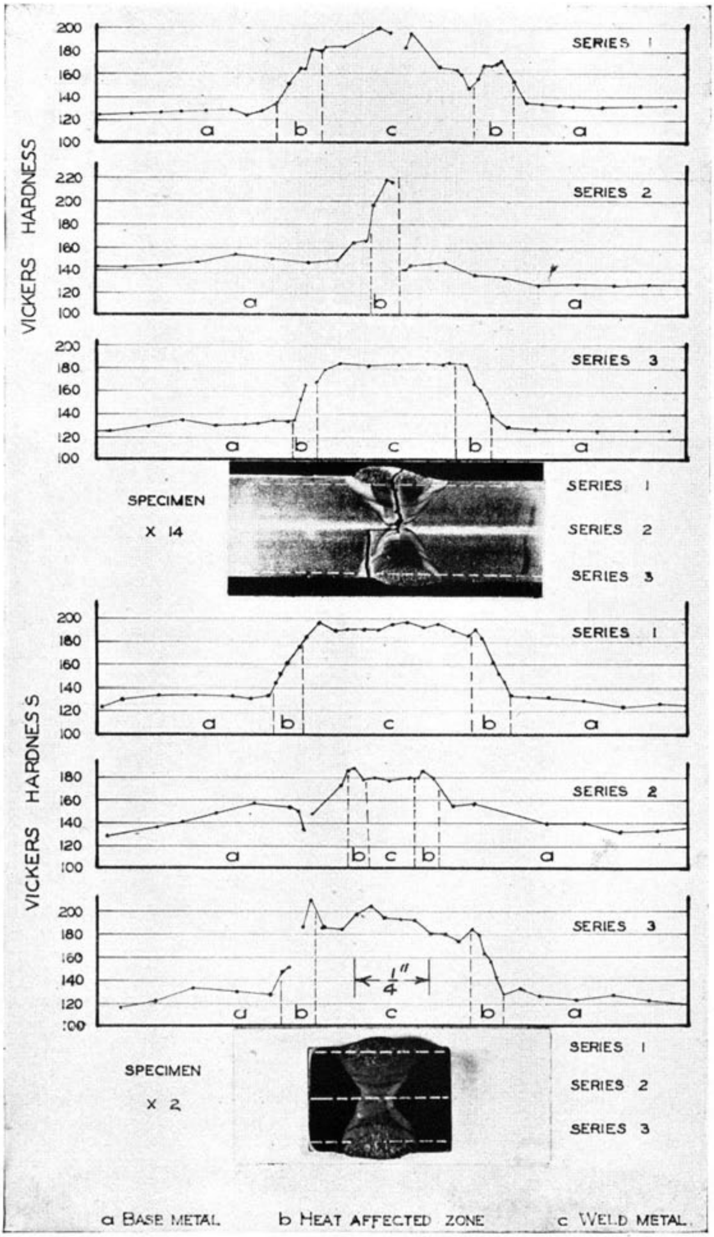


FIG. 6. HARDNESS DIAGRAMS FOR X2 AND X14

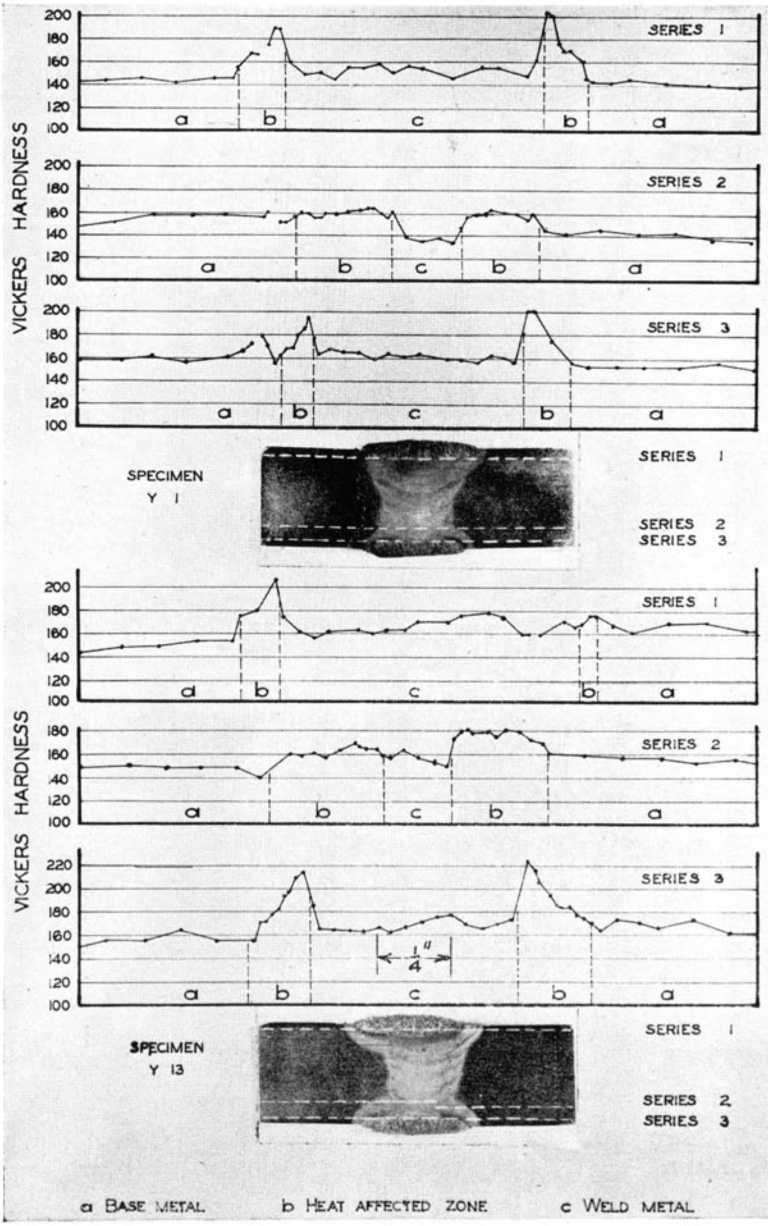


FIG. 7. HARDNESS DIAGRAMS FOR Y1 AND Y13

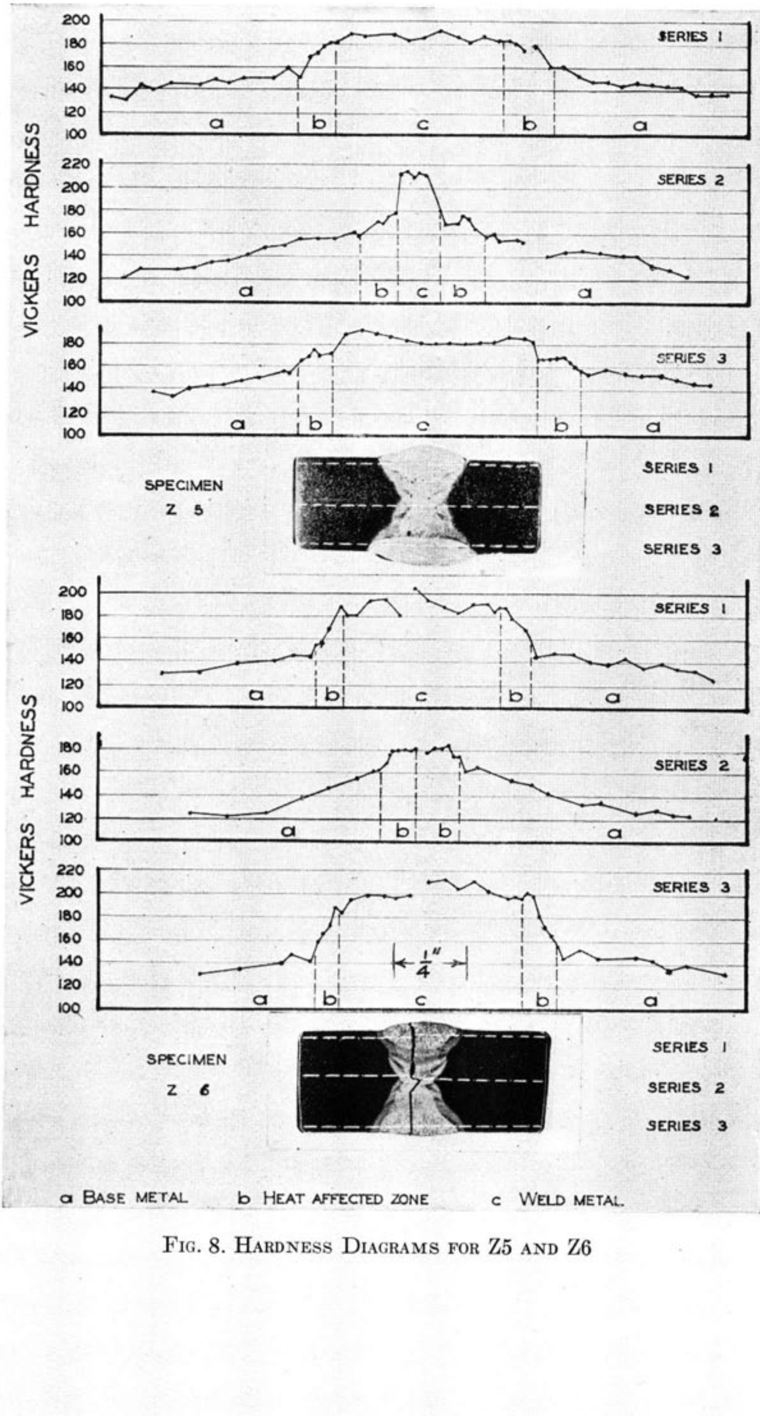


FIG. 8. HARDNESS DIAGRAMS FOR Z5 AND Z6

plate on both sides, and the area of the transverse section is greater at the middle than at the edge of the weld. Moreover, there is a small but sometimes abrupt change in section at the edge of the reinforcement that acts as a stress raiser extending the full width of the specimen. This being true, failure may be expected to occur at the edge of the reinforcement unless the weld metal is considerably weaker in fatigue than the base plate. The x-ray examination of the basic specimens showed only very minor flaws. As shown by Table 6, all specimens in the basic series failed either at the edge of the reinforcement or away from the weld. This indicates that the weld metal was at least fairly good for all of the basic specimens. In contrast with this, ten of the thirteen X specimens and eleven of the fourteen Z specimens broke in the weld at the increased section, and away from the stress raiser at the edge of the reinforcement. This indicates that the weld metal was significantly weaker in fatigue than the base metal. Only two of the fourteen Y specimens, Y6 and Y13, broke in the weld. Both were significantly weaker than the others of the group to which they belonged. It should be noted, however, that a specimen might break in the weld metal and still develop an average fatigue strength since, while failure actually took place in the weld metal, failure might have been impending either at the edge of the reinforcement or away from the weld. Likewise, failure at the edge of the reinforcement or away from the weld does not necessarily indicate a high fatigue strength, because a flaw might occur in the weld at the edge of the reinforcement or in the plate either adjacent to the weld or at some other section. In general, however, the specimens that broke at the edge of the reinforcement or in the base plate away from the weld had a relatively high fatigue strength. The probable causes of the low fatigue strength of the individual specimens of the various series are discussed in Sections 5 and 6.

5. *Metallurgical Studies.*—Metallurgical studies were made of the butt welds after they had been tested to failure in fatigue. As shown in Fig. 2, the details of the grooves and the welding procedure differed for the various series. The base plates, while of the same grade of steel, differed slightly in composition, as shown by the chemical analyses of Table 1.

The major object of the metallurgical studies was to correlate the type of fatigue failure and the fatigue strength of the specimens with the microstructure, hardness, and observable defects.

TABLE 8
VICKERS HARDNESS NUMBERS FOR BASE AND WELD METAL
Two Specimens Each of X, Y, and Z Series

Specimen No.	Series No.	Unaffected Base Metal			Heat-Affected Zone		Weld Metal		
		Minimum	Maximum	Average	Minimum	Maximum	Minimum	Maximum	Average
X14	1	125	134	130	135	181	147	200	175
	2	127	166	140	175	217*			
	3	124	134	130	135	184	168	185	182
X2	1	116	135	128	135	190	180	197	190
	2	133	174	140	177	187	177	180	179
	3	123	134	130	130	209	175	206	190
Y1	1	139	146	142	145	203	146	161	155
	2	135	157 (161)	150	150	164	134	150	140
	3	144	162 (179)	155	158	200	156	169	162
Y13	1	141	178	160	168	204	156	177	165
	2	142	161	155	145	180	150	163	155
	3	149	175	162	155	224	162	180	168
Z5	1	131	162	150	150	184	183	193	187
	2	121	162	145	159	178	210	214	212
	3	135	158	150	158	176	170	192	185
Z6	1	126	148	140	155	190	182	(205)	190
	2	122	165	140	160	185			
	3	131	154	142	150	202	185	214	205

*A hardness value of 230 occurred in a laminated area with carbon segregation. Values in parentheses () were obtained adjacent to fatigue cracks where cold working probably increased the hardness.

Hardness Measurements

Hardness measurements on polished-and-etched specimens of several butt welds, representative of the three series, were made subsequent to the fatigue tests. The resulting hardness diagrams, given in Figs. 6, 7, and 8, are for the sections indicated on the macrographs. The following notation is used in this and subsequent figures: (a) unaffected base metal, (b) heat-affected base metal, (c) weld metal.

The hardness surveys of series 1 and 3 on all of the specimens were made along a line 0.05 inch from the plate surfaces. Series 2 surveys were made at the root of the weld, which was at mid-thickness of the plate for the X and Z specimens, but was just above the sealing bead placed at the bottom of the U groove for the Y specimen, as shown in Fig. 7. Hardness values for the two specimens each of the X, Y, and Z series are given in Table 8 and a summary of these data is given in Table 9.

Specimens X2 and X14

Reference to Fig. 6 and Table 8 shows that the average hardness of the base metal for specimens X2 and X14 was 130 Vickers for series 1 and 3, and 140 Vickers for series 2. The weld metal was harder

TABLE 9
VICKERS HARDNESS NUMBERS FOR X, Y, AND Z SPECIMENS
Summary Based Upon Two Specimens From Each Series

Series	Base Metal						Weld Metal			
	Unaffected			Heat-Affected		Maximum Variation in One Specimen	Minimum	Maximum	Average	Maximum Variation in One Specimen
	Minimum	Maximum	Average	Minimum	Maximum					
X	116	174	133	130	217	93	147	206	183	53
Y	135	178	154	145	224	83	134	180	158	35
Z	121	165	145	150	202	80	182	214	196	44

than the base plate, the average values for a series varying from 175 to 190 Vickers numbers. The maximum hardness in region (b), the heat-affected zone of specimen X14, was 217 Vickers at the left side of the crack in series 2 of Fig. 6. However, a hardness of 230 Vickers was obtained in the heat-affected zone on the right side just above the row of indents in series 2. This higher hardness was associated with the segregation of carbon in the region of the lamination shown in the macrograph. The maximum hardness of the heat-affected zone of specimen X2 was 209 Vickers, which was obtained in the series 3 survey.

The base metal increased in hardness near the heat-affected area as shown in series 2 for both X specimens. A study of the microstructure of the base metal in these regions gave no indication of the cause for this increase in hardness.

The maximum variation in hardness between the unaffected base metal and the heat-affected zone was 93 Vickers numbers for both X specimens. (This does not include an area of segregated carbon in X14 where the hardness was 106 Vickers numbers greater than the hardness of the unaffected base metal.) This is a considerable variation in hardness for a steel of such low average carbon content.

Specimens Y1 and Y13

The average hardness of the unaffected base metal of specimen Y1 was 149 Vickers, and the range in hardness was from 135 to 162 Vickers. This does not include a reading of 179 Vickers in the cold-worked region next to the fatigue crack. The unaffected base metal of Y13 had the high hardness values of 178 and 175 Vickers, respectively, in series 1 and 3, and the average hardness values were somewhat

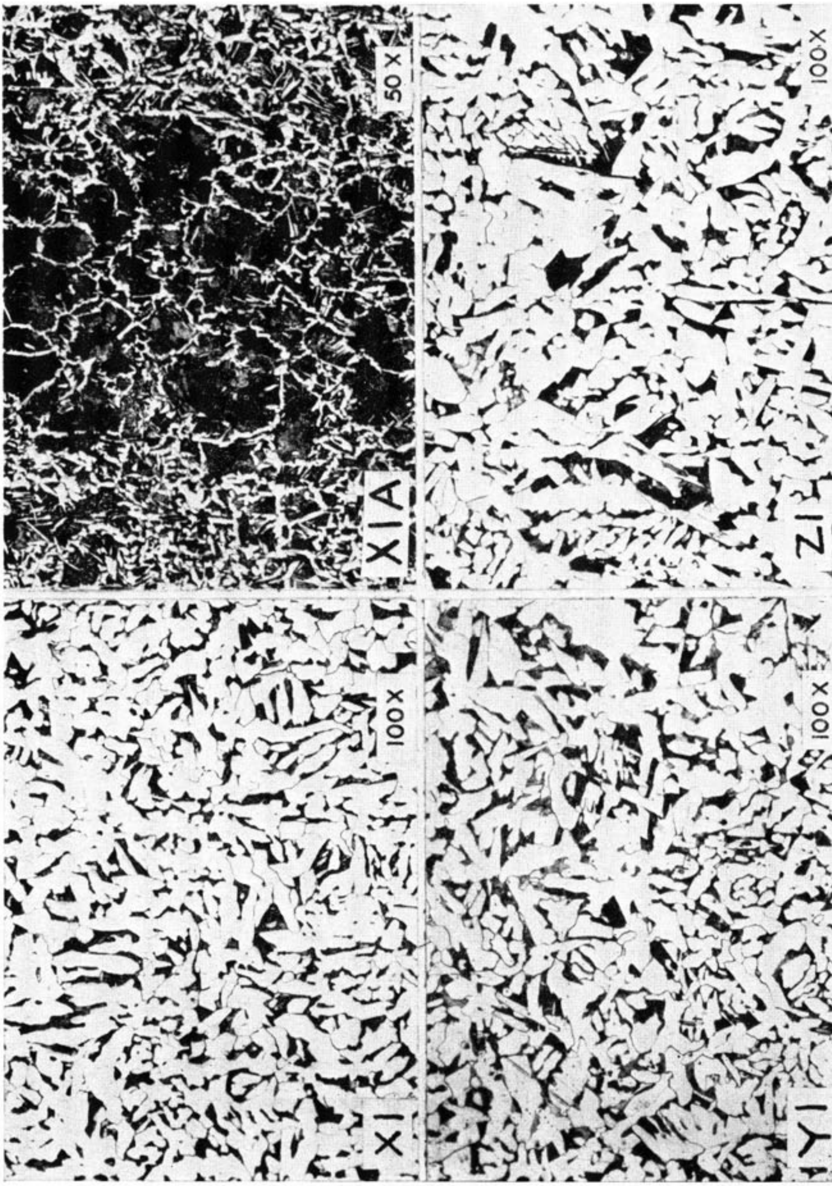


FIG. 9. TYPICAL MICROSTRUCTURES OF BASE METAL IN X, Y, AND Z SPECIMENS

higher than for specimen Y1. For both specimens, the weld metal was slightly harder than the unaffected base metal, except for series 2 of specimen Y1, where this condition was reversed. The greater width of the welds in series 1 and 3 of the Y specimens as compared with those of the X and Z specimens, is shown by the macrographs and the hardness contours.

The maximum hardness in the heat-affected zone occurred adjacent to the last beads to be deposited. These were traversed by the series 1 and 3 hardness surveys. The hardness maxima in the heat-affected zone were 203 Vickers for specimen Y1, series 1, and 224 Vickers for specimen Y13, series 3. The maximum variations in hardness between the unaffected and the heat-affected base metal were 68 and 83 Vickers numbers, respectively, for specimens Y1 and Y13.

Specimens Z5 and Z6

The average hardness values of the unaffected base metal were 148 and 140 Vickers, respectively, for Z5 and Z6. The minimum hardness values for the unaffected base metal were practically the same for both specimens, and there was an increase in hardness near the heat-affected zone. The weld metal was considerably harder than the unaffected base metal, and the maximum hardness was greater for the weld metal than for the heat-affected zone for both Z specimens. The maximum hardness values of the heat-affected base metal were 184 and 202 Vickers, respectively, for Z5 and Z6; and the maximum variations in the hardness of the base metal were 63 and 80 Vickers numbers, respectively, for the two specimens.

Relative Hardness of X, Y, and Z Specimens

The hardness values of the specimens of the various series are compared in Table 9, which is a summary of the values given in Table 8. The hardness in cold-worked areas adjacent to fatigue cracks and in areas of segregation were not included in this summary. It is apparent from this table that the hardness characteristics were very similar for the X, Y, and Z specimens.

Microstructures

A survey of the microstructure in the base metal, the heat-affected zone, and the weld metal was made for specimens X14, Y6, and Z11. Typical areas in the various zones were photographed and are shown in Figs. 9 to 14.

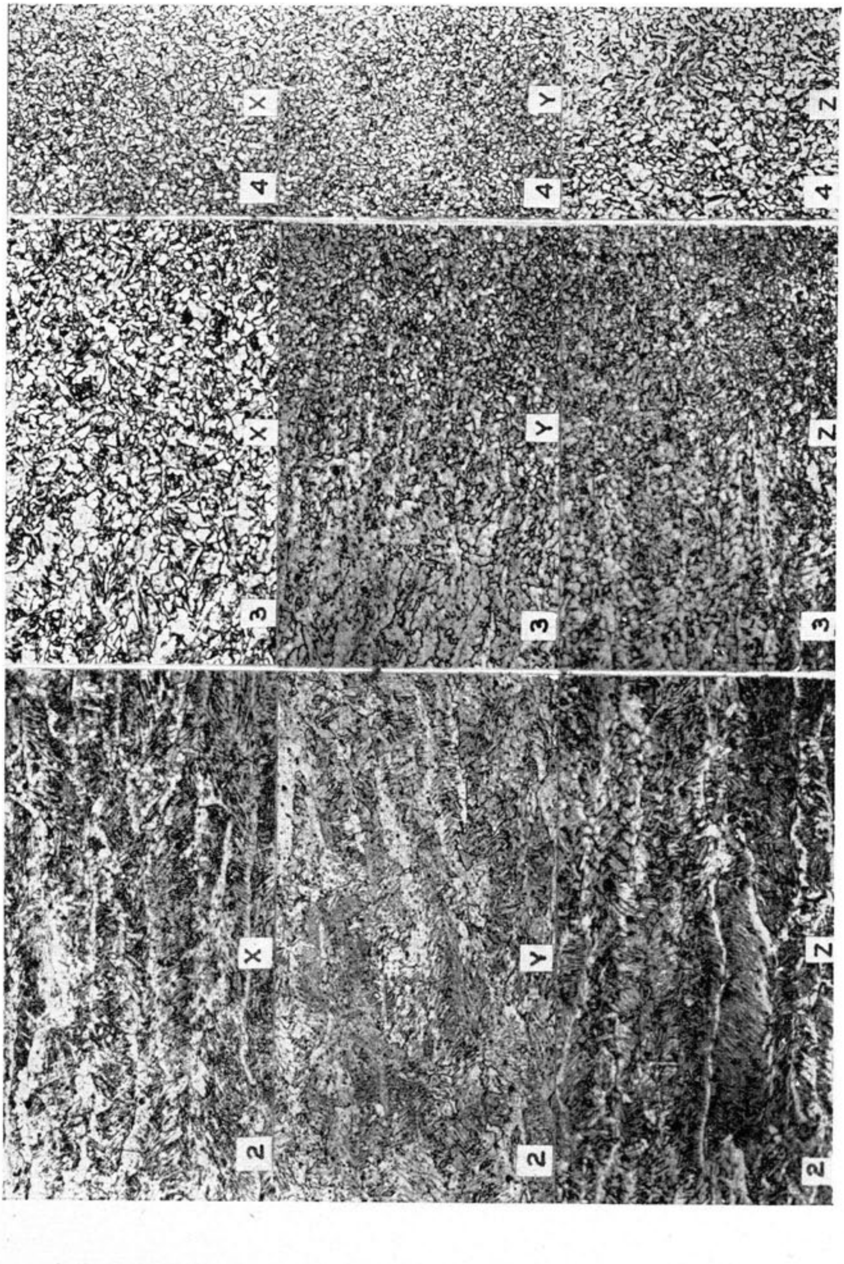


FIG. 10. TYPICAL MICROSTRUCTURES OF WELD METAL IN X, Y, AND Z SPECIMENS

Regions X1, Y1, and Z1 of Fig. 9 show microstructures typical of the unaffected base plates of the X, Y, and Z specimens. The character of the segregated areas, typical of several of the X specimens, is also shown in region X1A of the same figure. The increase in carbon content and the grain size in the region of the lamination are also shown. There was an unusual accumulation of non-metallic inclusions in this region. Aside from the presence of both large and small laminations in the X specimens, and of small laminations in the Y and Z specimens, the base metals were of similar structure.

Typical microstructures of the weld metal of specimens X, Y, and Z are shown in Fig. 10. The location of the regions shown in Fig. 10 are given in the macrographs of Figs. 11, 12, and 13. For all specimens, region 2 had a columnar structure, region 4 was a recrystallized zone, and region 3 was a junction between these two types of structures.

Region 5 of Figs. 11, 12, and 13 shows the coarse grain of the heat-affected zone adjacent to the columnar weld metal of the outside bead. The grain size of this region appeared to decrease in the order of Y, Z, and X. Region 6 of the same figures shows the junction of the unaffected base metal and the heat-affected zone which, in general, appeared quite similar for the three groups of specimens, X, Y, and Z. Region 7 shows the base metal at or near the fusion line in the interior of the weld. In the case of X and Y specimens, this was a fine-grain area which had received a double heat treatment. In the case of the Z specimen, Fig. 13, this region was not reheated by the subsequent weld deposit. Grains were found close to region 7 of specimen Z that were even larger than those present adjacent to the outside weld deposit, shown in region 5 of the same figure. Region 8 of Fig. 13 had a grain structure so coarse that it could be detected in the macrograph. This condition was characteristic of the Z specimens and also occurred in a number of the X specimens examined. For the Y specimens, the heat-affected base metal adjacent to the weld had a normalized structure except for the region adjacent to the last beads deposited. The doubly heat-treated base metal of the Y6 specimen is shown at the right in Fig. 14, and is compared with the recrystallized weld metal, which is shown at the left of the same figure. The grain size appeared to be the same for both, and the higher carbon content of the base metal was apparent in the pearlite areas at the grain boundaries. Small particles of slag and occasional pearlite areas occurred in the weld metal.

The base metal of the Z specimens was most free of laminations, but it contained a considerable number of slag stringers. The base

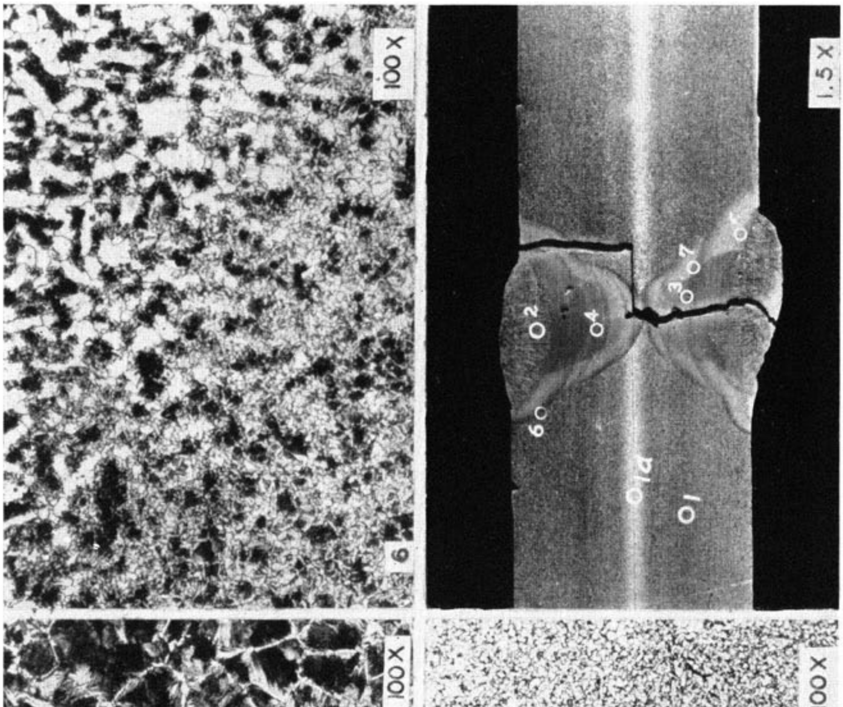


FIG. 11. TYPICAL MICROSTRUCTURES OF HEAT-AFFECTED BASE METAL OF SPECIMEN X14

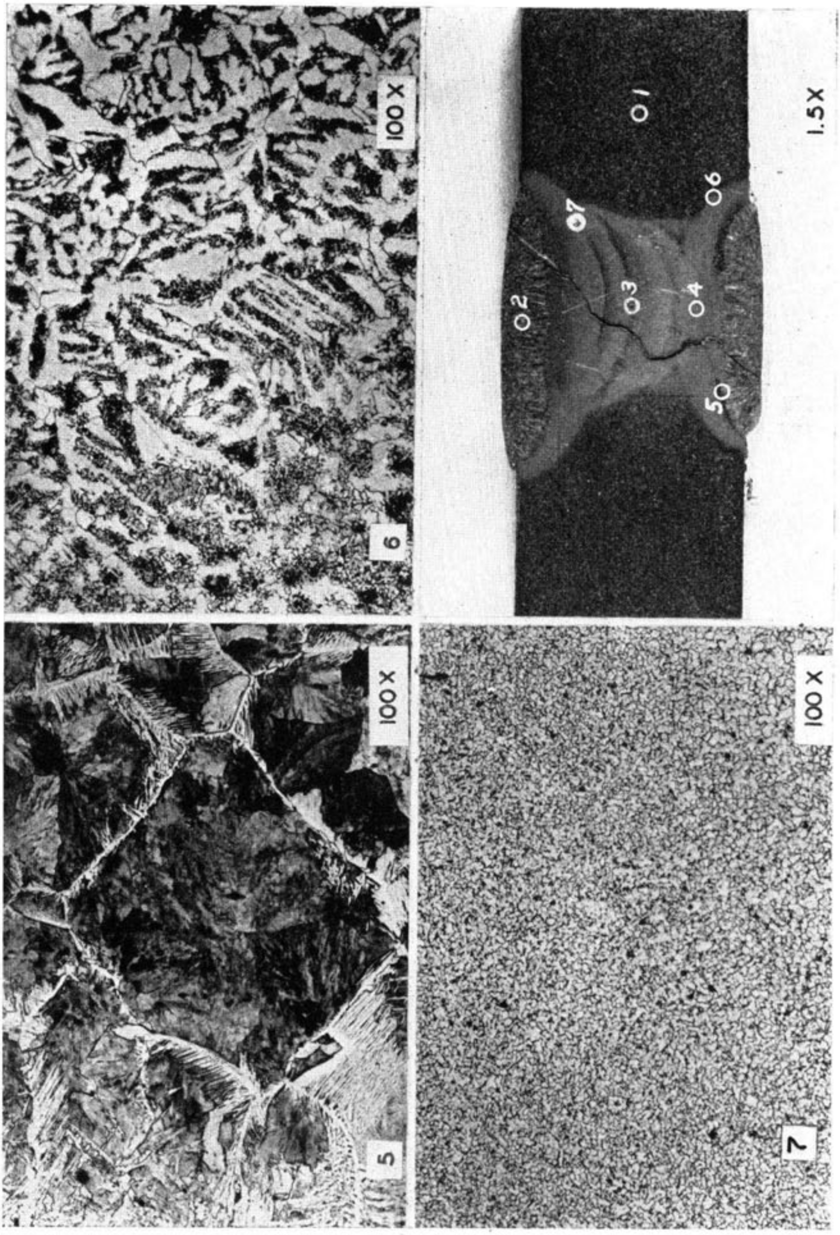


FIG. 12. TYPICAL MICROSTRUCTURES OF HEAT-AFFECTED BASE METAL OF SPECIMEN Y6

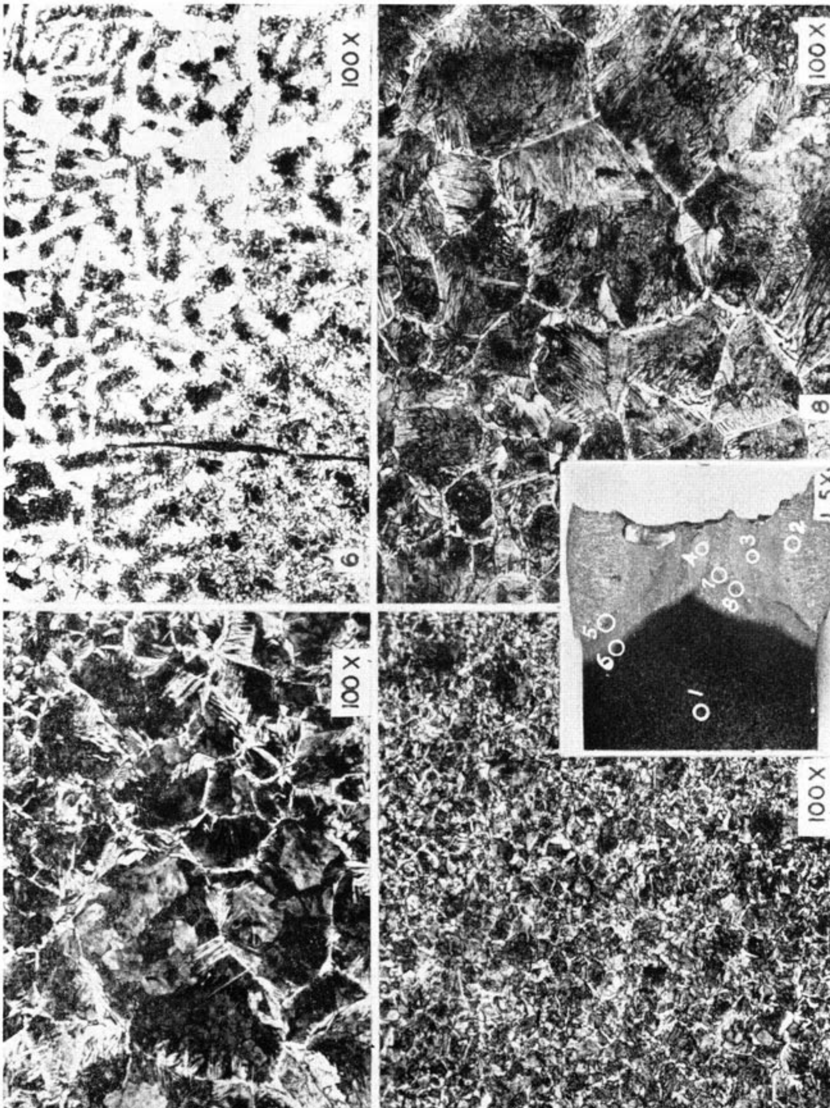


Fig. 13. Typical Microstructures of Heat-Affected Base Metal of Specimen Z5

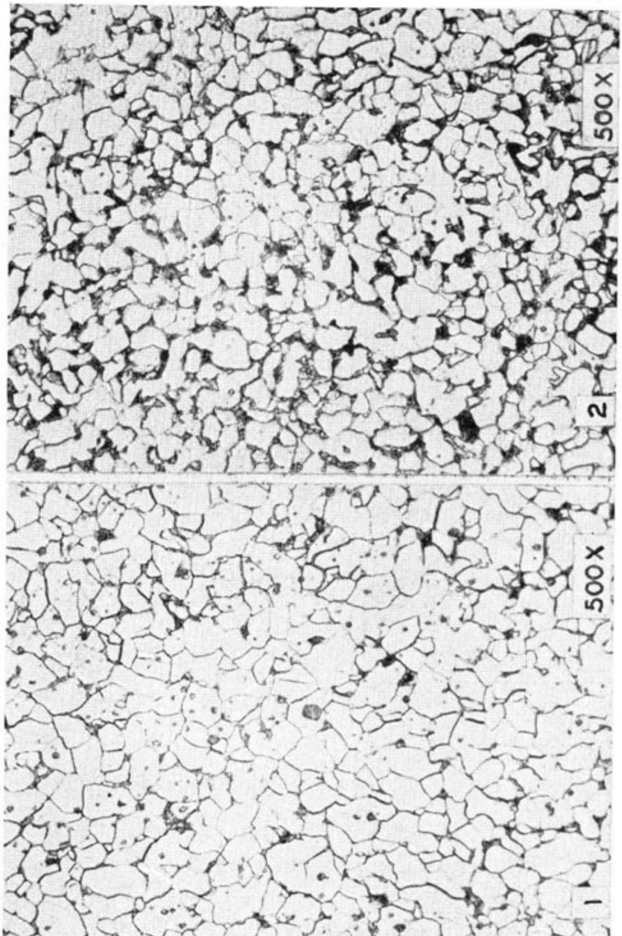


FIG. 14. MICROSTRUCTURES OF RECRYSTALLIZED WELD AND HEAT-AFFECTED BASE METAL OF SPECIMEN Y6

1. Recrystallized Weld Metal
2. Doubly Heat-Treated Base Metal

TABLE 10
COMPARISON OF AREAS OF COLUMNAR AND RECRYSTALLIZED WELD METAL AND HEAT-AFFECTED ZONE

Specimen No.	Area of Weld, sq. in.	Percentage of Total Weld Metal in Two Outer Beads	Percentage of Un-recrystallized Weld Metal Exclusive of Two Outer Beads	Area of Heat-Affected Zone, sq. in.
X1	0.39	56	5.7	0.12
X2	0.41	52	6.5	0.12
X7	0.41	50	4.3	0.14
X11	0.38	51	2.3	0.20
X14	0.36	48	1.2	0.14
X15	0.40	53	4.5	0.15
	Av. 0.39	51	4.5	0.15
Y1	0.59	46	3.0	0.22
Y3	0.63	43	10.5	0.23
Y6	0.56	48	5.6	0.22
Y13	0.60	51	5.2	0.24
	Av. 0.59	47	6.0	0.23
Z5	0.43	45	19.0	0.16
Z6	0.40	57	5.6	0.15
Z13	0.38	60	7.0	0.15
Z15	0.49	50	11.0	0.20
	Av. 0.42	52	11.5	0.16

TABLE 11
LOCATION OF FATIGUE FRACTURES
X, Y, and Z Series

Series	Number of Failures at Edge of Weld	Number of Failures Through Weld	Number of Failures Partly in Weld and Partly in Plate	Number of Failures in Plate
X	2	7	4	1
Y	11	1	2	1
Z	3	5	5	1

metal of the Y specimens appeared to be banded, and showed the presence of slag stringers and minor laminations. The X specimens had the largest laminations, and the carbon segregation surrounding the laminations indicated that the portion of the ingot used for the plate probably contained a secondary pipe.

The grain size of the coarse-grained, heat-affected zone was a maximum for the Y specimens, intermediate for the Z specimens, and a minimum for the X specimens. This difference in grain size for the coarse-grain zone was an indication of the relative heat effects of the finishing bead, and was not related to the grain-coarsening tendency of the base metal. The Y specimens had the largest areas of coarse-grained, heat-affected base metal adjacent to the last weld beads placed on both sides of the plate. The outer weld deposits were considerably wider than the adjacent previously-placed deposits in the joint. A comparison of these zones for a number of the specimens is made in Table 10. The quantities compared include: area of weld; percentage of total weld metal in two outer beads, one on each side of plate; percentage of weld metal, exclusive of two outer beads not recrystallized; and area of heat-affected zone. These data were obtained from planimeter measurements of the macrographs.

There was a considerable variation in the data on different specimens for each series but the average values showed trends that are of interest. The volume of weld metal* placed in the joint increased in the order of X, Z, and Y, and the volume of heat-affected metal increased in the same order. The average percentage of un-recrystallized weld metal in the interior of the weld, exclusive of the as-cast metal of the last two beads of each joint, increased in the order of X, Y, and Z.

Fatigue Fractures

A classification of fatigue failures, on the basis of the regions in which the fractures occurred, is given in Table 11. The X and Z specimens failed generally in the weld metal, and the Y specimens failed generally at the edge of the weld. The fractures for specimens X6, X10, X11, X14, Z3, Z6, Z11, Z12, and Z15 started in the weld metal, and extended into the heat-affected zone; the fractures for Y3 and Y13 started in the heat-affected zone, and extended into the weld metal.

The failures through the weld metal are characterized by large and small fisheye areas distributed over the fracture surface as indicated in Figs. 15, 16, and 17. Lack of root penetration, which appears as a band at mid-section extending across the full width of the section, seems to be a frequent cause of failure. There were laminations at mid-section of some of the X specimens which may or may not have affected the fatigue strength. An example of this latter condition is given in Fig. 18, showing the fracture surface of X14 at a magnification of $1\frac{1}{2}\times$. The macrograph of the fracture at the right shows that lack of root penetration was the cause of failure of a portion of the specimen, and at the left side the line across the fracture surface is identified as the site of a major lamination. Figure 19 shows the fracture of specimen X15, an outstanding example of a fracture which started at the internal stress raiser resulting from a lack of root penetration.

*The large volume for the Y specimens can be attributed, at least in part, to the single U type of weld.

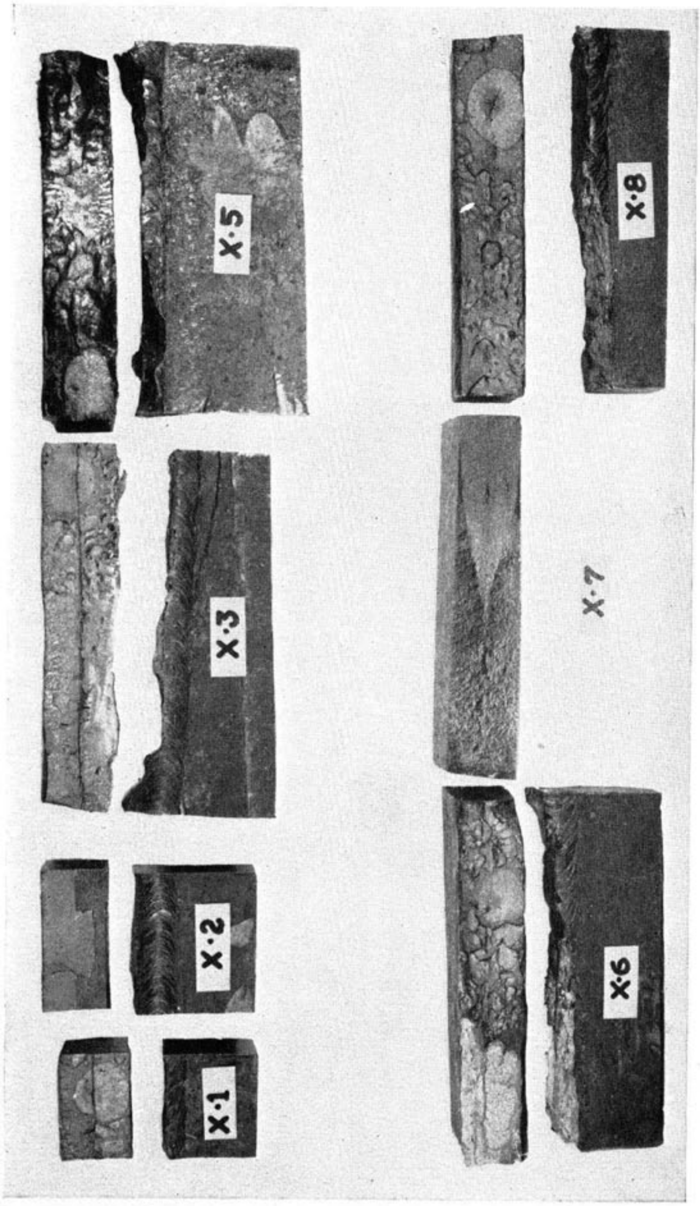


FIG. 15 (a). FRACTURES OF THE X SPECIMENS

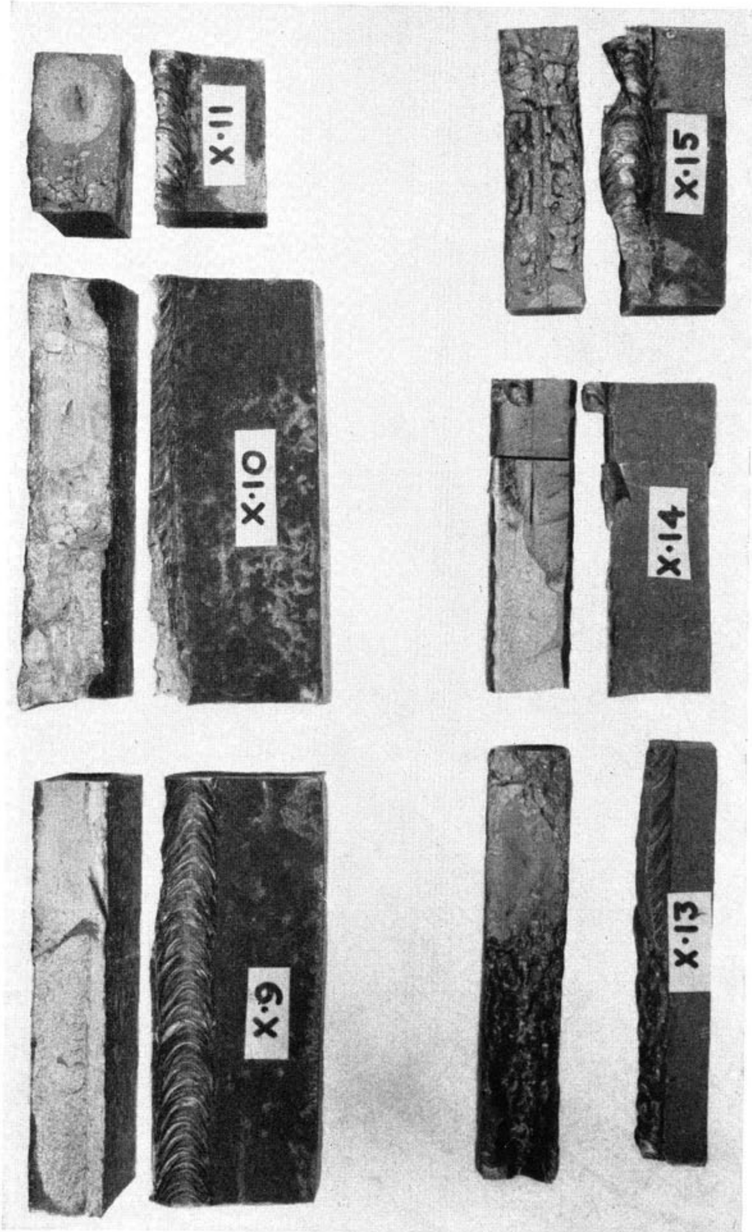


FIG. 15 (b). FRACTURES OF THE X SPECIMENS

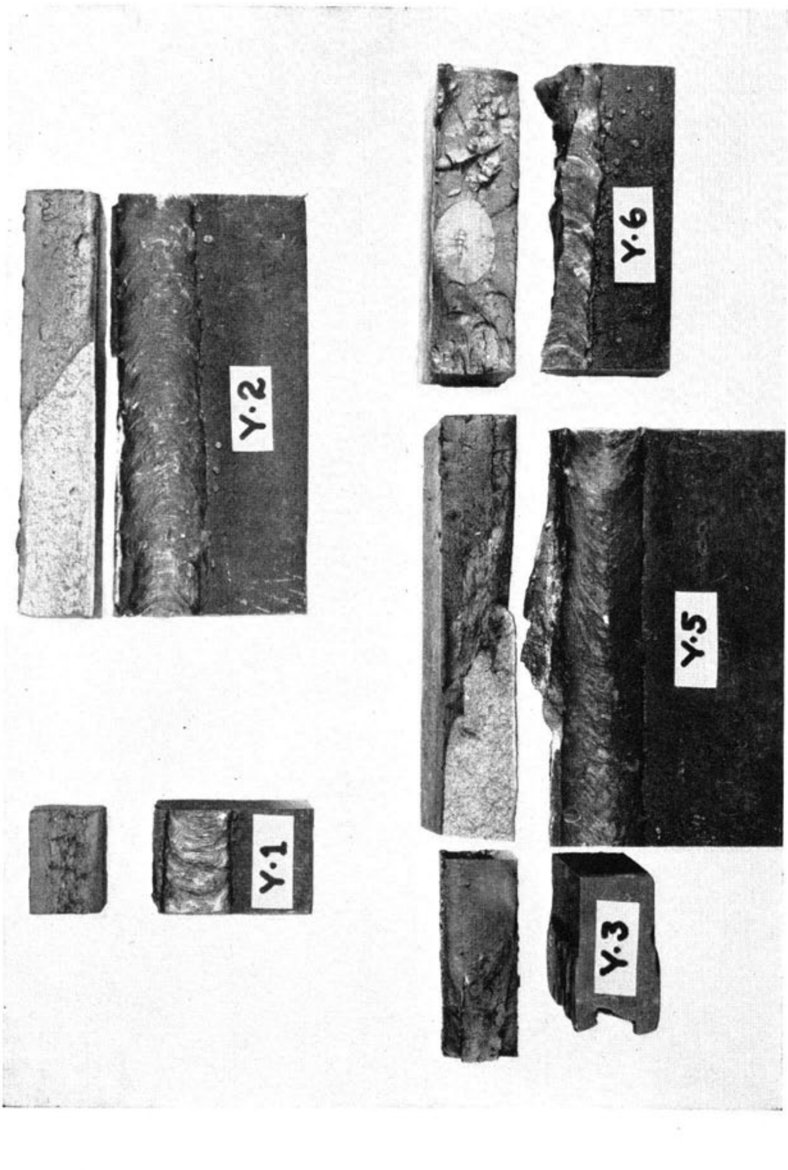


FIG. 16 (a). FRACTURES OF THE Y SPECIMENS

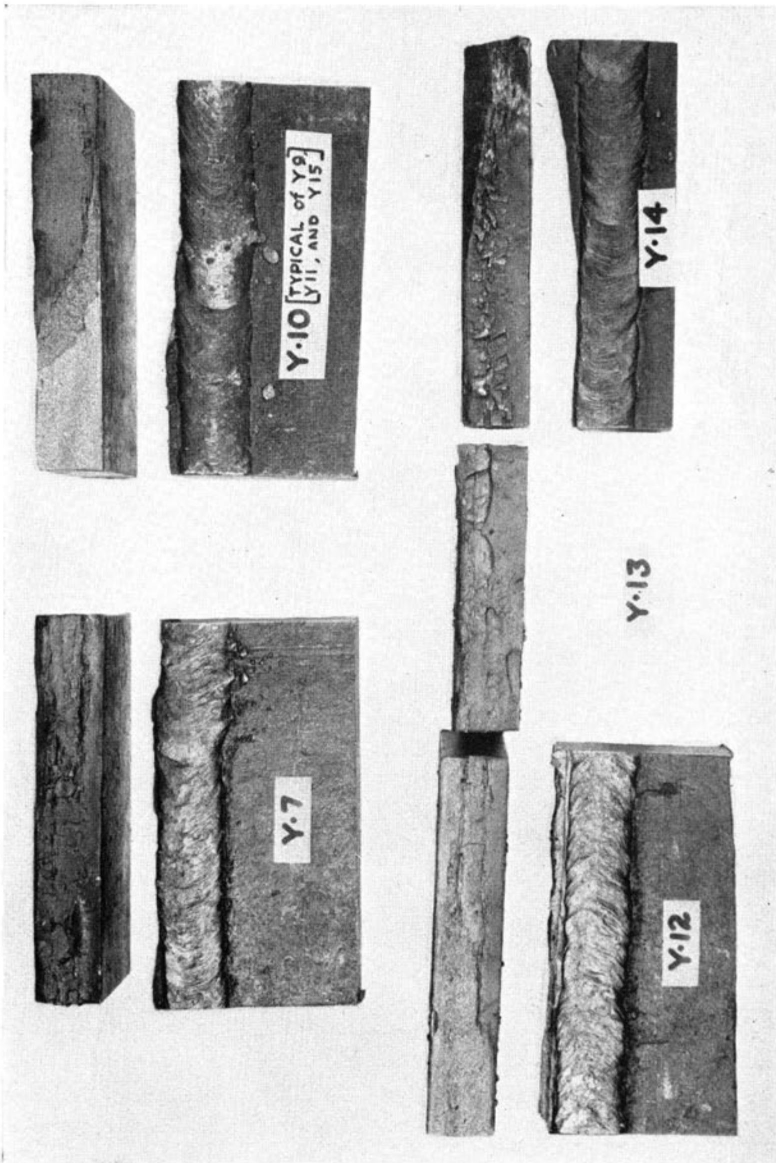


FIG. 16 (b). FRACTURES OF THE Y SPECIMENS

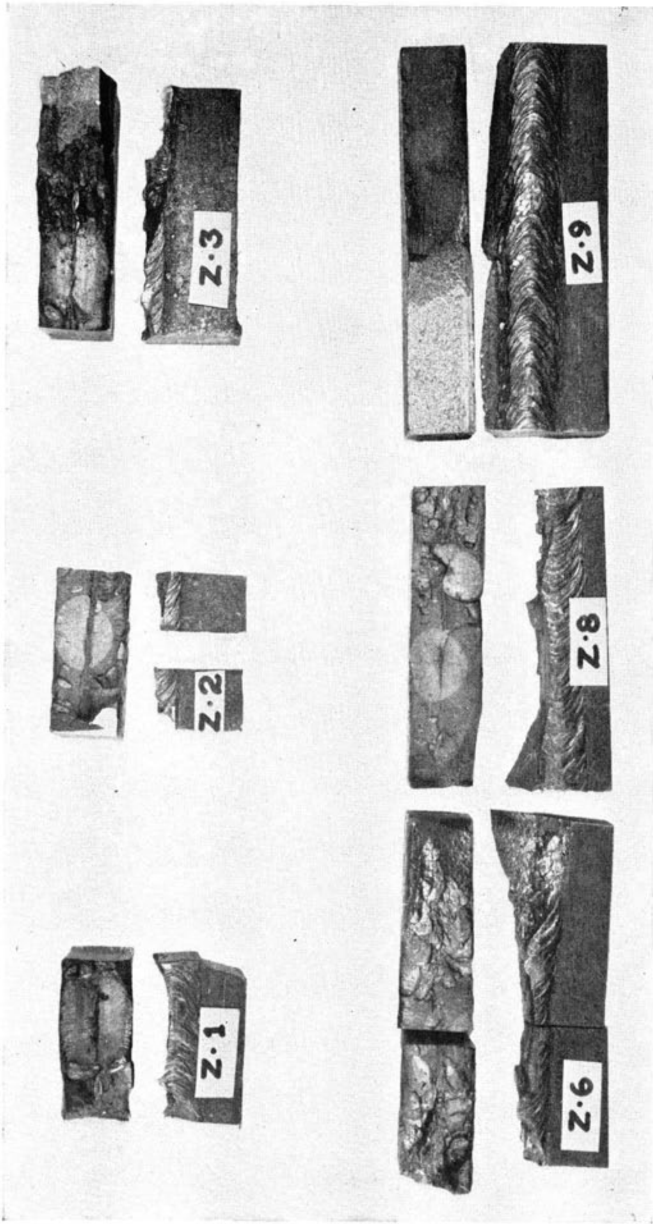


FIG. 17 (a). FRACTURES OF THE Z SPECIMENS

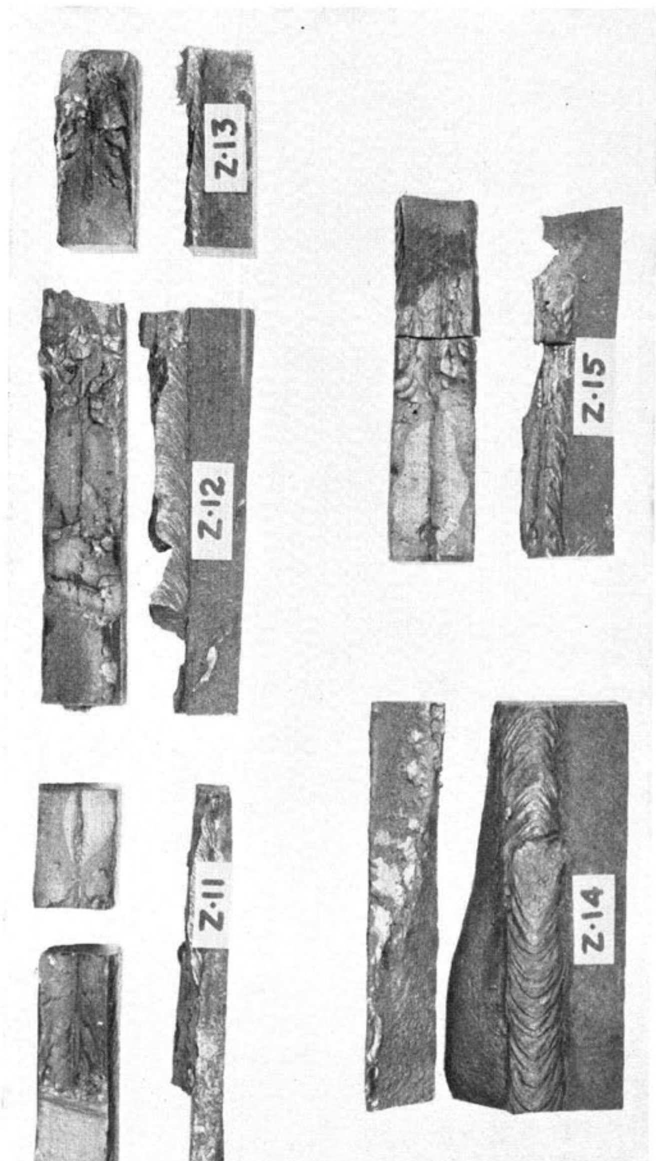


FIG. 17 (b). FRACTURES OF THE Z SPECIMENS

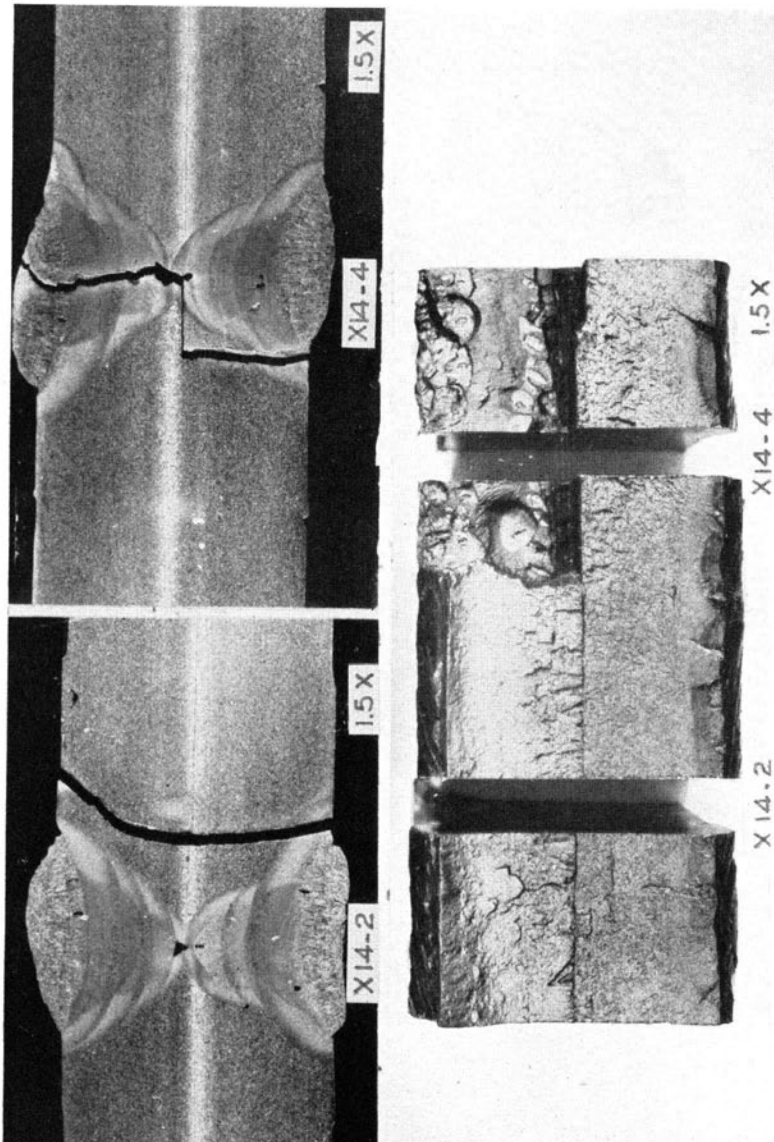


Fig. 18. Macrographs and Fracture Surface of Specimen X14 Showing Lack of Root Penetration and Effect of Lamination on Path of Fracture

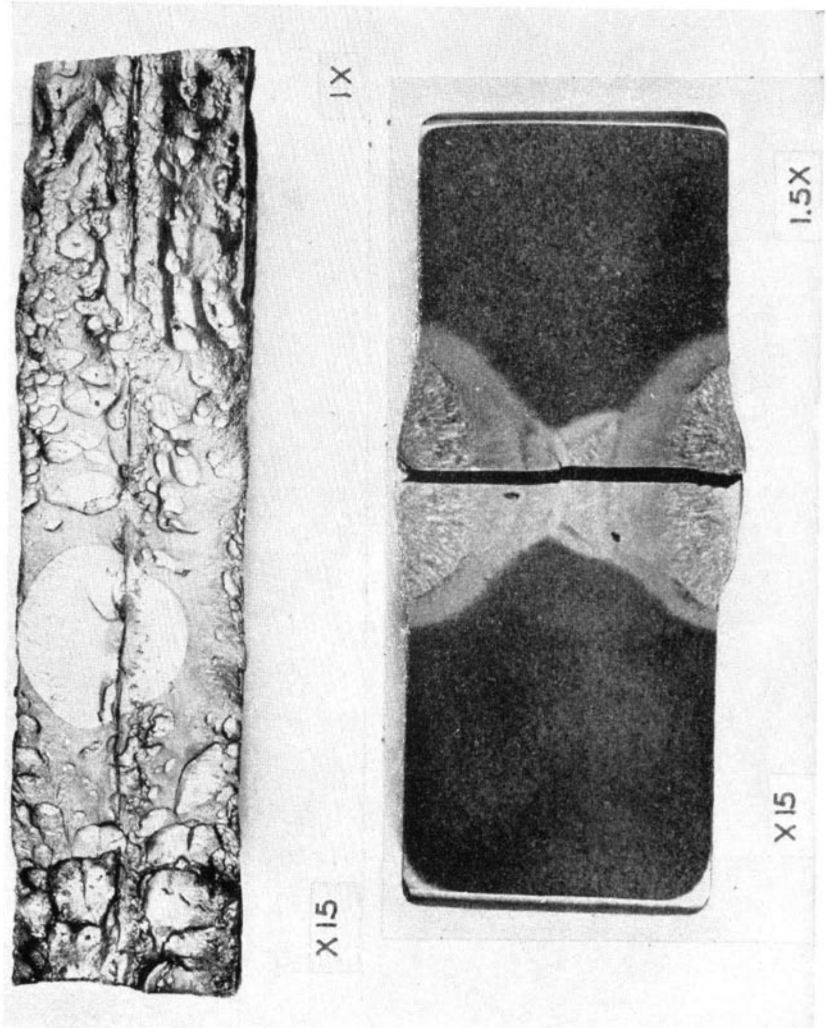


FIG. 19. MACROGRAPHS AND FRACTURE SURFACE OF SPECIMEN X15 SHOWING EFFECT OF LACK OF ROOT PENETRATION ON FATIGUE FAILURE

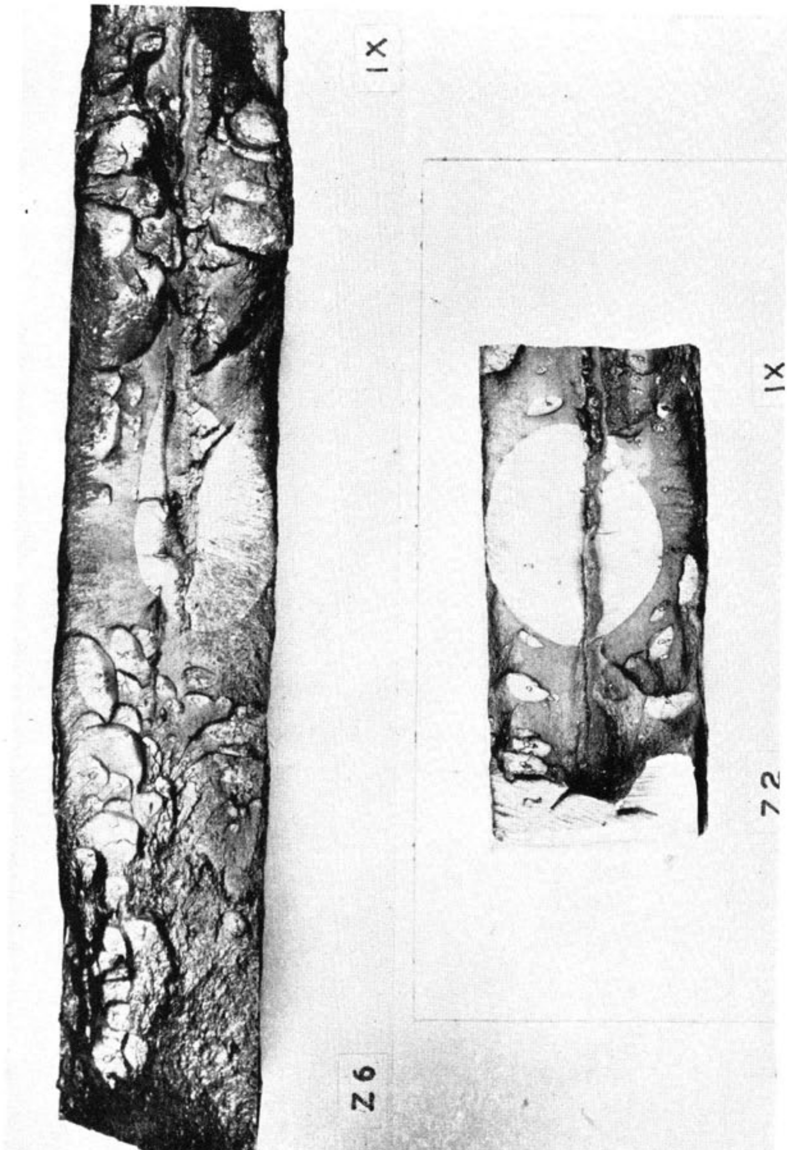


FIG. 20. FRACTURE SURFACES OF SPECIMENS Z2 AND Z6 SHOWING LACK OF ROOT PENETRATION

Most of the Z specimens failed in the weld due to a lack of root penetration. The fracture surfaces of specimens Z2, Z6, Z7, Z11, and Z15, are shown in Figs. 20 and 21. There were no major laminations in the base metal of the Z specimens, and the unfused portion of the base metal at the root of the weld could easily be distinguished in these fracture surfaces.

Figure 16 shows that Y6 was the only one of the Y group that failed entirely through the weld metal. A survey of the weld-metal area indicated greater porosity in Y6 than was found in other Y specimens, but in no case was lack of root penetration found in the specimens of this group.

The Y specimens in general failed in the heat-affected zone at the edge of the weld, and the large number of minor laminations (banded structure) in the base metal was indicated in the fracture surface as a woody structure, which was quite pronounced for several Y specimens, as shown in Fig. 16.

Of the X specimens, X2 and X9 failed at the edge of the weld rather than through the weld metal, and they had higher fatigue strengths than the other X specimen tested on the same cycles. The macrograph of X2, Fig. 22, shows some porosity, but good root penetration. Specimen X7, which failed in the plate at a considerable distance from the weld, also had some porosity and good penetration, as shown in the same figure. Apparently where good root penetration was obtained, and porosity was not too great, the failure occurred at the edge of the weld where the reinforcement acted as a geometrical stress raiser rather than in the weld metal.

Defects and Their Relation to the Path of Failure

A major lamination is here defined as a separation of the plate for a considerable length, due to a large porous or piped zone in the ingot which was not completely welded during hot rolling. Several of the X specimens contained such laminations, and specimen X14 has been previously noted as an outstanding example. The path of the fatigue crack may be entirely changed* in direction by such a lamination, as shown in the macrograph of specimen X14-4 in Fig. 18. The meanderings which such laminations may take are shown in the micrographs of specimen X14-2, Fig. 23. Cracks were developed by the inclusions, not only along the laminated area, but also normal to the direction of stress. It appears that the laminated condition caused the failure to

*Macrograph X14-2 and X14-4 are of parallel sections of specimen X14.

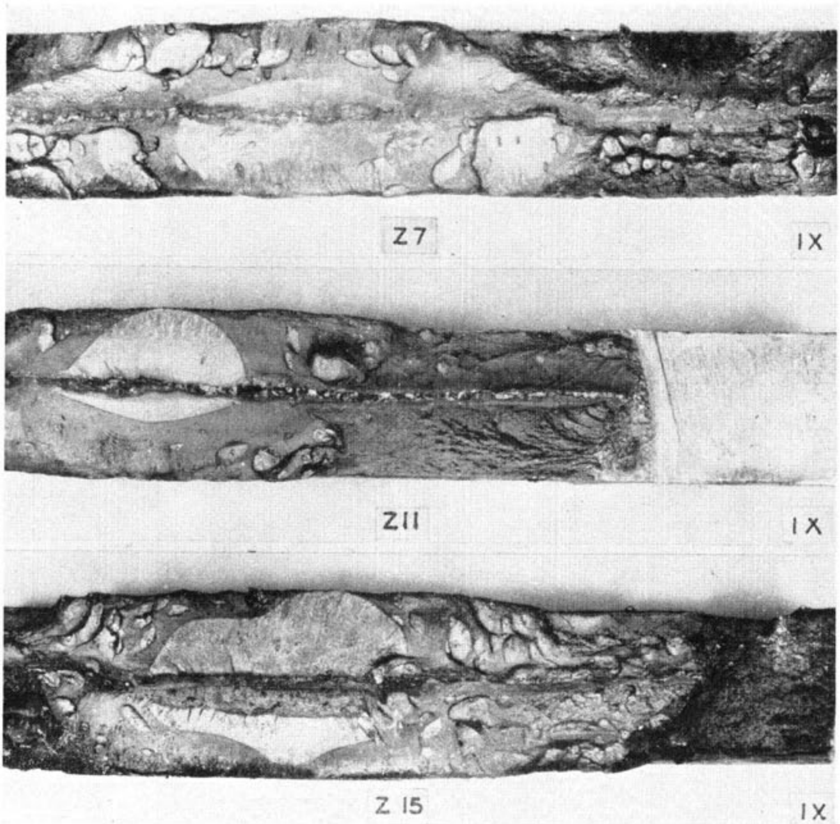


FIG. 21. FRACTURE SURFACES OF SPECIMENS Z7, Z11, AND Z15 SHOWING LACK OF ROOT PENETRATION

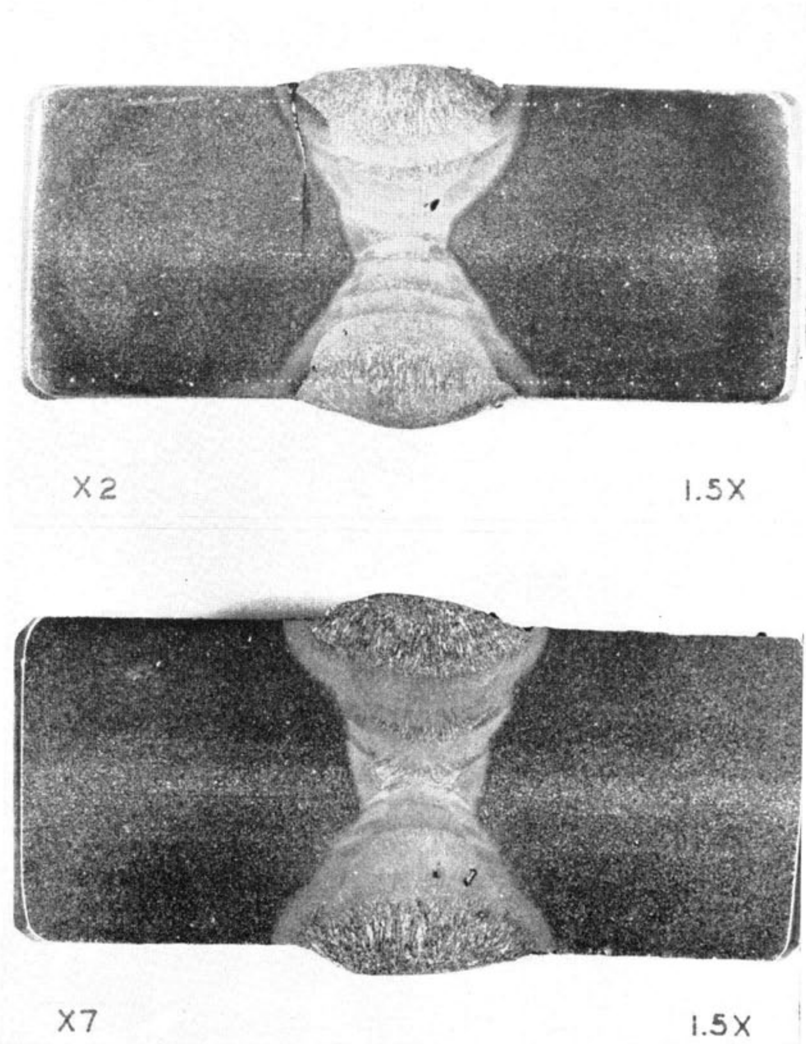


FIG. 22. MACROGRAPHS OF SPECIMENS X2 AND X7
SHOWING GOOD ROOT PENETRATION

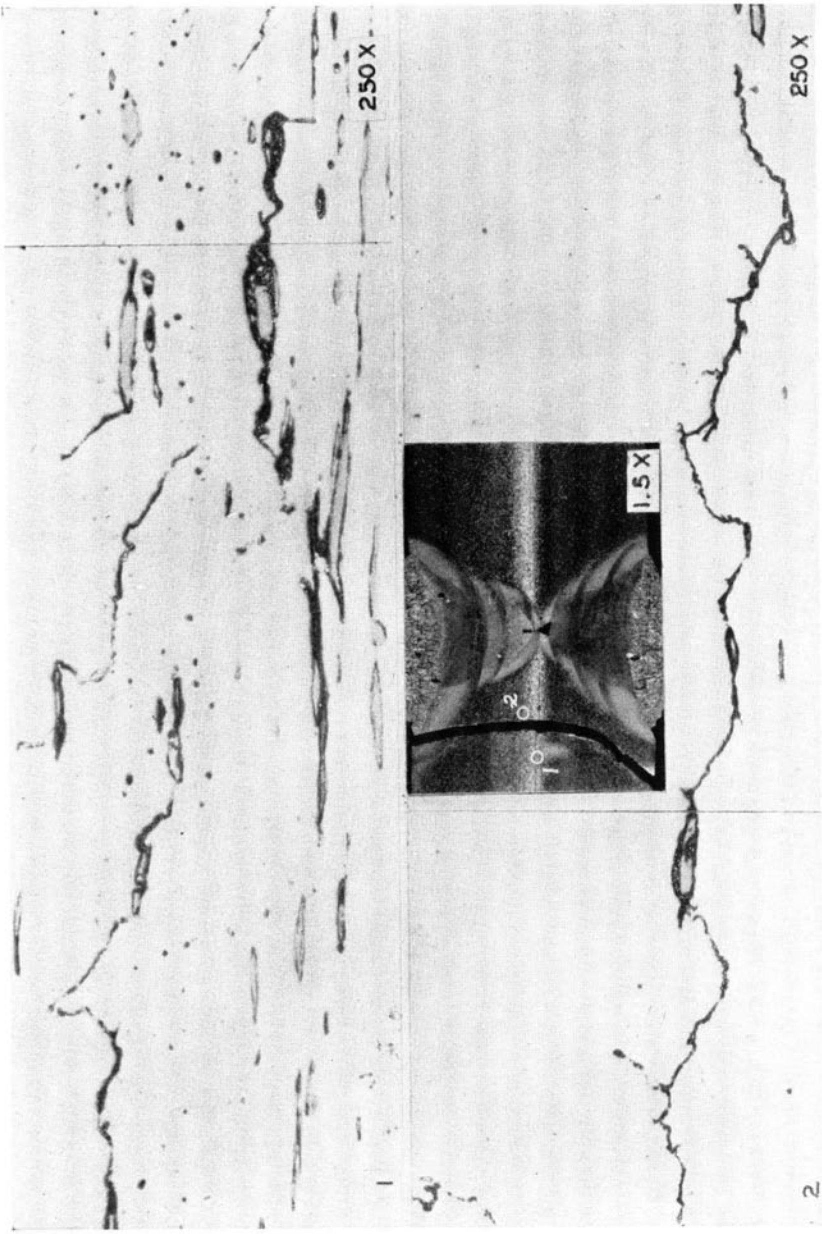


FIG. 23. MICROGRAPHS OF LAMINATED REGION OF SPECIMEN X14

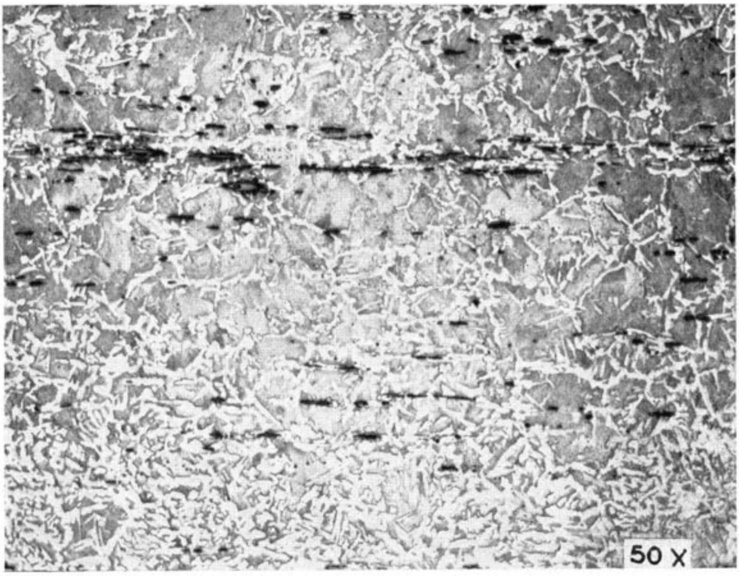


FIG. 24. MICROGRAPH OF BANDED OR MINOR LAMINATED BASE METAL OF SPECIMEN X14, ALSO TYPICAL OF Y AND Z SPECIMENS

take the path shown in the center of the macrograph of X14-4, Fig. 18, for a portion of the specimen.

The small laminations or banded structure found in all of the base plates were a result of incomplete welding of secondary blowholes during hot rolling of the ingot. These blowholes were well distributed over the ingot, and appeared in the plate with a high frequency as short laminations which were the site of segregations of non-metallic particles. Figure 24 is a micrograph of such an area in specimen X14, which is typical of a similar condition in all of the X, Y, and Z specimens. The thermal gradient produced in the heat-affected zone of the base metal during welding caused these small laminations to open to their greatest width at or near the weld deposit, as shown by the arrows on the macrograph of specimen X1, Fig. 25. A similar condition existed in specimen Y1, as shown in Fig. 26. Region 1 is a micrograph of laminations which widened to their greatest extent at the left side, next to the weld deposit. One such lamination is shown in region 2, where the weld metal at the left is the terminus of the partially-opened lamination.

Region 3 of Fig. 26 is a micrograph of a small lamination in specimen Y13, which opened in the heat-affected zone, and caused a

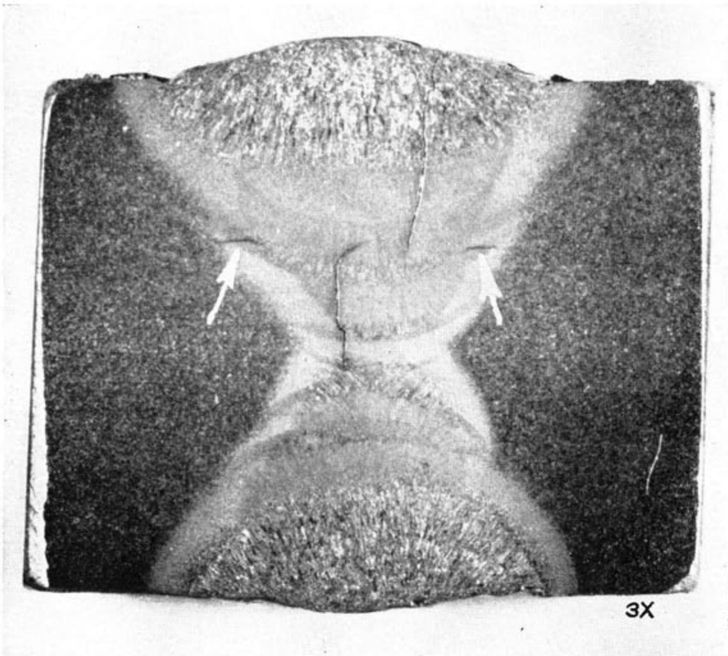


FIG. 25. MACROGRAPH OF SPECIMEN X1 WITH ARROWS SHOWING OPENING OF MINOR LAMINATIONS IN HEAT-AFFECTED ZONE

crack to start at one end. Region 4 is another area showing an opened lamination in the heat-affected zone of specimen Y13, which acted as an internal stress raiser.

The Z specimens also showed the presence of a large number of these small laminations and occasionally a few of near major proportions.

One effect of laminations was to cause a block type of fracture, as shown in Fig. 27, which occurred in specimens X14, Y1, and Z5. Although it is not clearly established, it appears possible that the weakening of the plate by such internal stress raisers may have hastened the formation of the fatigue crack which caused failure.

A study of the distribution of the inclusions in the weld metal made on unetched, polished sections revealed an apparent accumulation of the non-metallic inclusions from the base metal in the region of the fusion line and at the surface of root beads, as shown in Fig. 28. The elongated inclusions in the base metal became spherical in the melt which chilled so rapidly as to prevent the escape of the inclusions to the slag cover on top of the molten weld deposit.

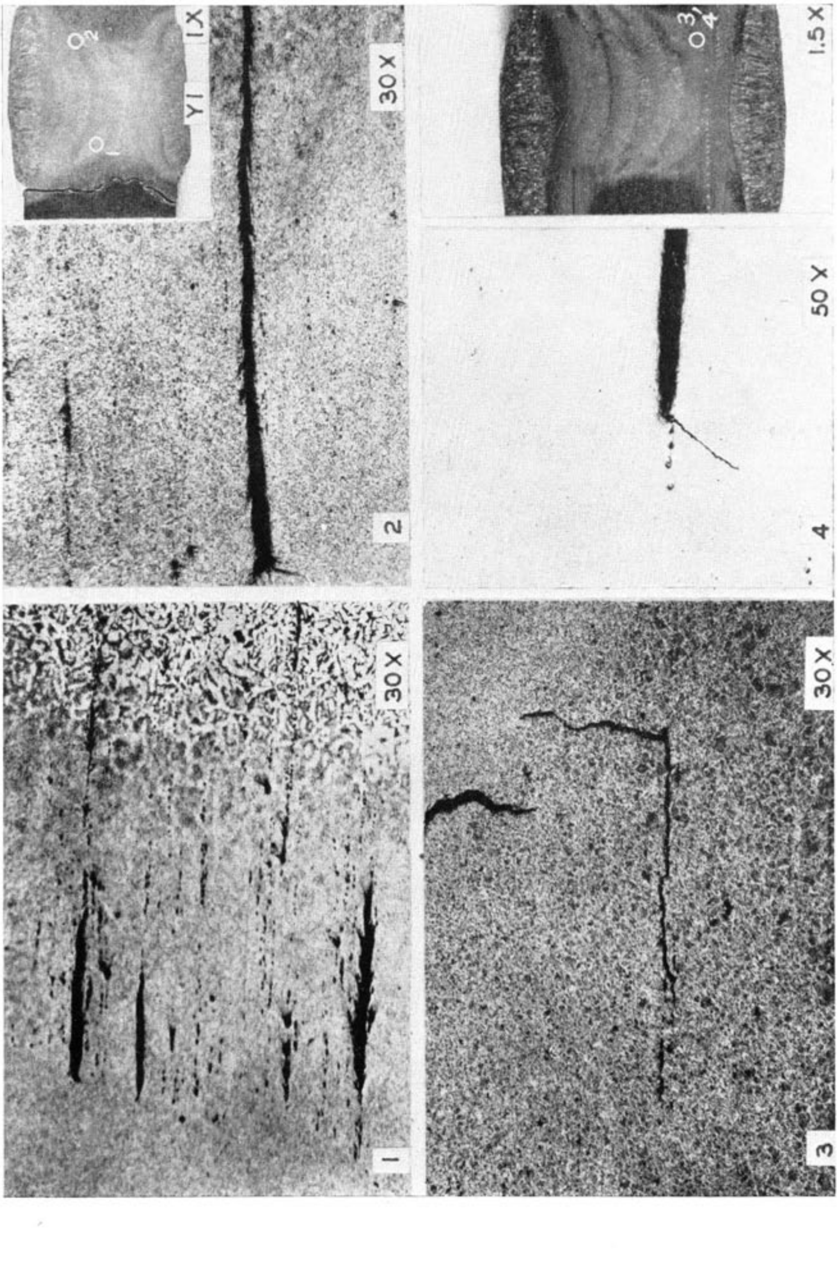


FIG. 26. MICROGRAPHS OF SPECIMENS Y1 AND Y13 SHOWING OPENING OF MINOR LAMINATIONS IN HEAT-AFFECTED ZONE

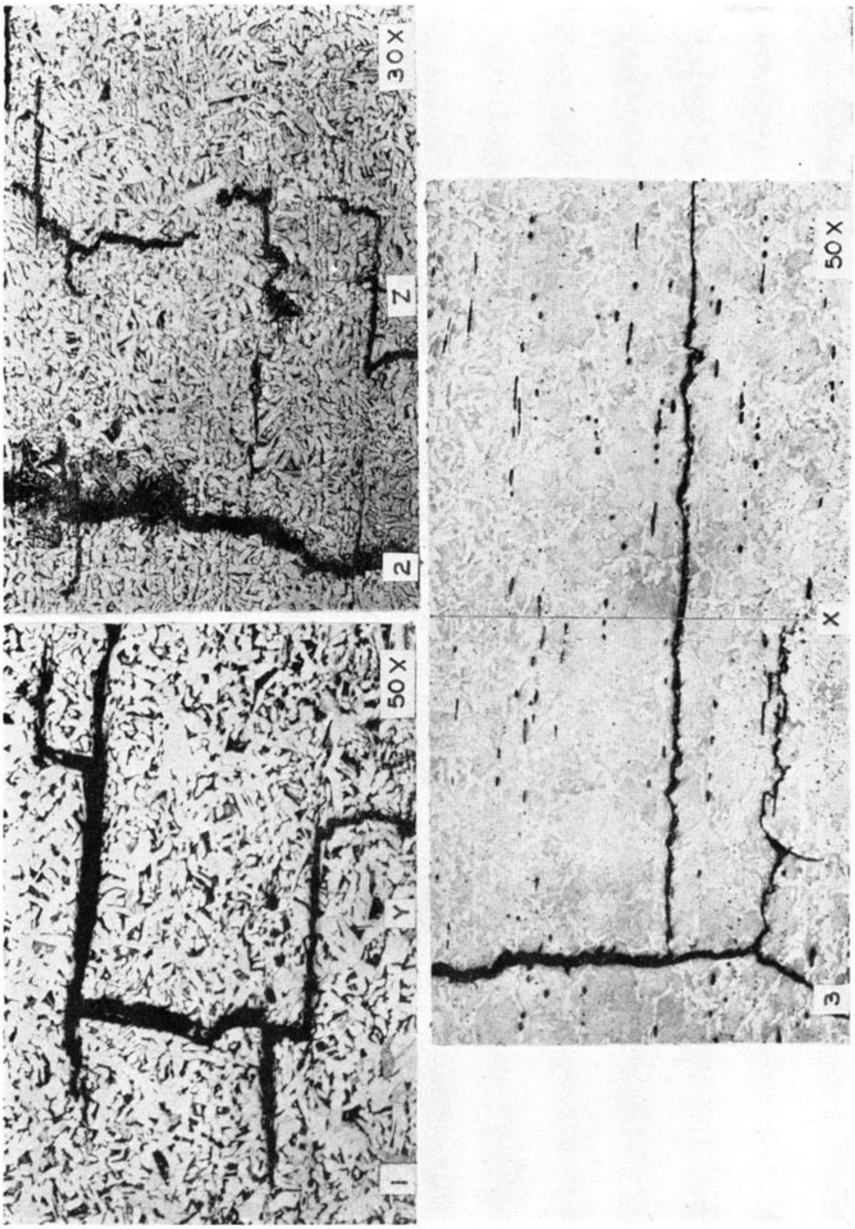


Fig. 27. Micrographs of Block Fracture Caused by Laminations in X, Y, and Z Specimens

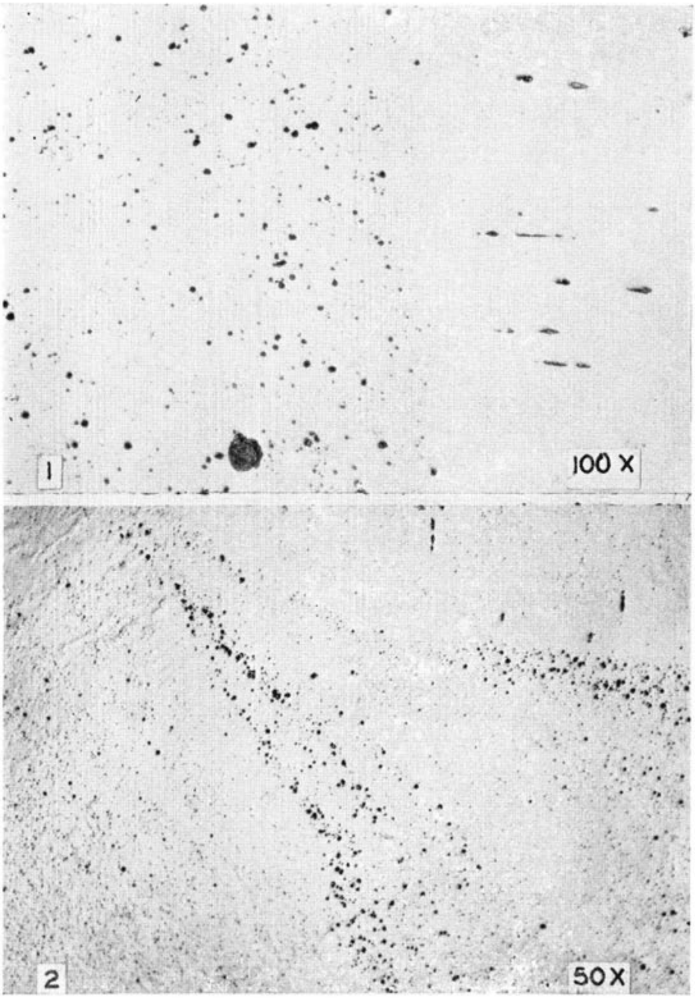


FIG. 28. MICROGRAPHS OF INCLUSIONS IN WELD METAL AT ROOT OF WELD

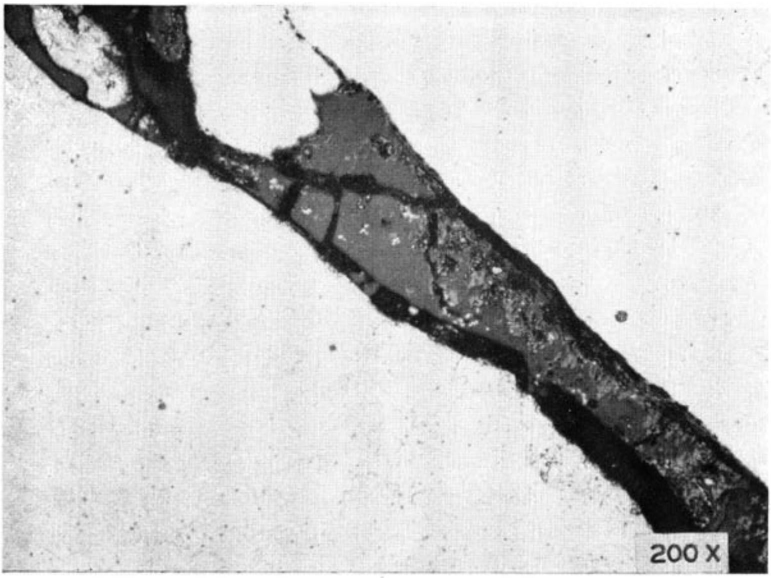


FIG. 29. MICROGRAPH OF ELECTRODE SLAG ON UNFUSED SCARF OF SPECIMEN Z11

Evidence of lack of root penetration in the X and Z specimens was shown in the fracture surfaces of Figs. 15 and 17. Figure 29 shows an area near the root of the weld of specimen Z11 where the slag from the electrode coating had not been removed before the weld metal was placed. The dark area in this micrograph is recognized as slag from the electrode coating by the small particles of weld-metal spatter which it contains. The left side of Fig. 30 shows the unfused root of specimen X14, and the right side shows the effect of the expanding gas in preventing root fusion and causing porosity in the weld subsequently laid down. Figure 31 shows a number of micrographs of unfused root areas in specimens Z5, Z6, and Z15. Even though the lack of fusion at the root of Z5 had a large stress-raising effect, failure occurred at the edge of the weld, indicating that the change in section acted as an even more effective stress raiser extending the full width of the specimen.

Porosity in the weld metal was found in various regions of the welds, and was due to the trapping of gas in the rapidly solidifying metal. Porosity is thus distinguished from unfused regions which occurred mainly at or near the fusion line and principally at the root of the double V weld. None of the welds examined were entirely free

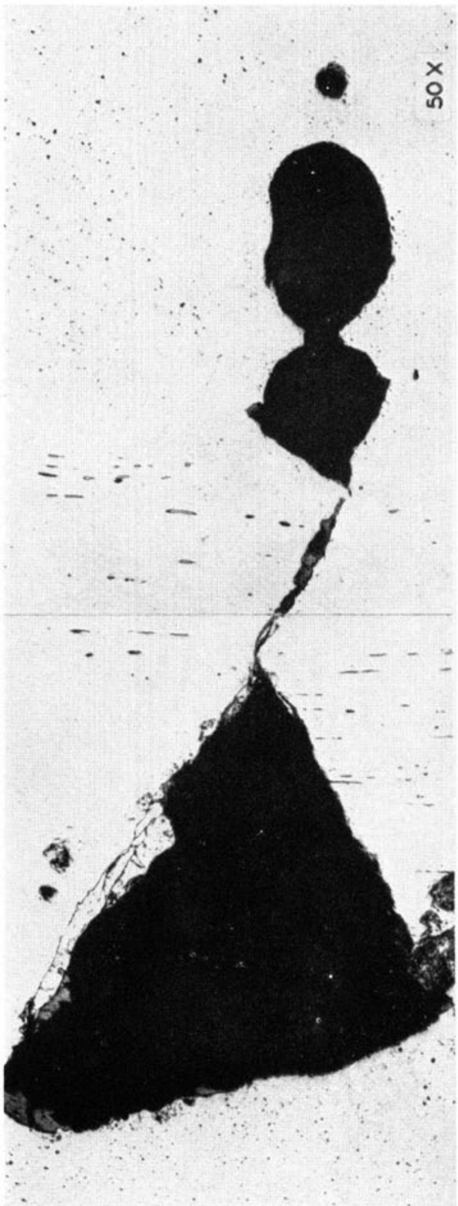


FIG. 30. MICROGRAPH OF UNFUSED ROOT OF WELD IN SPECIMEN X14

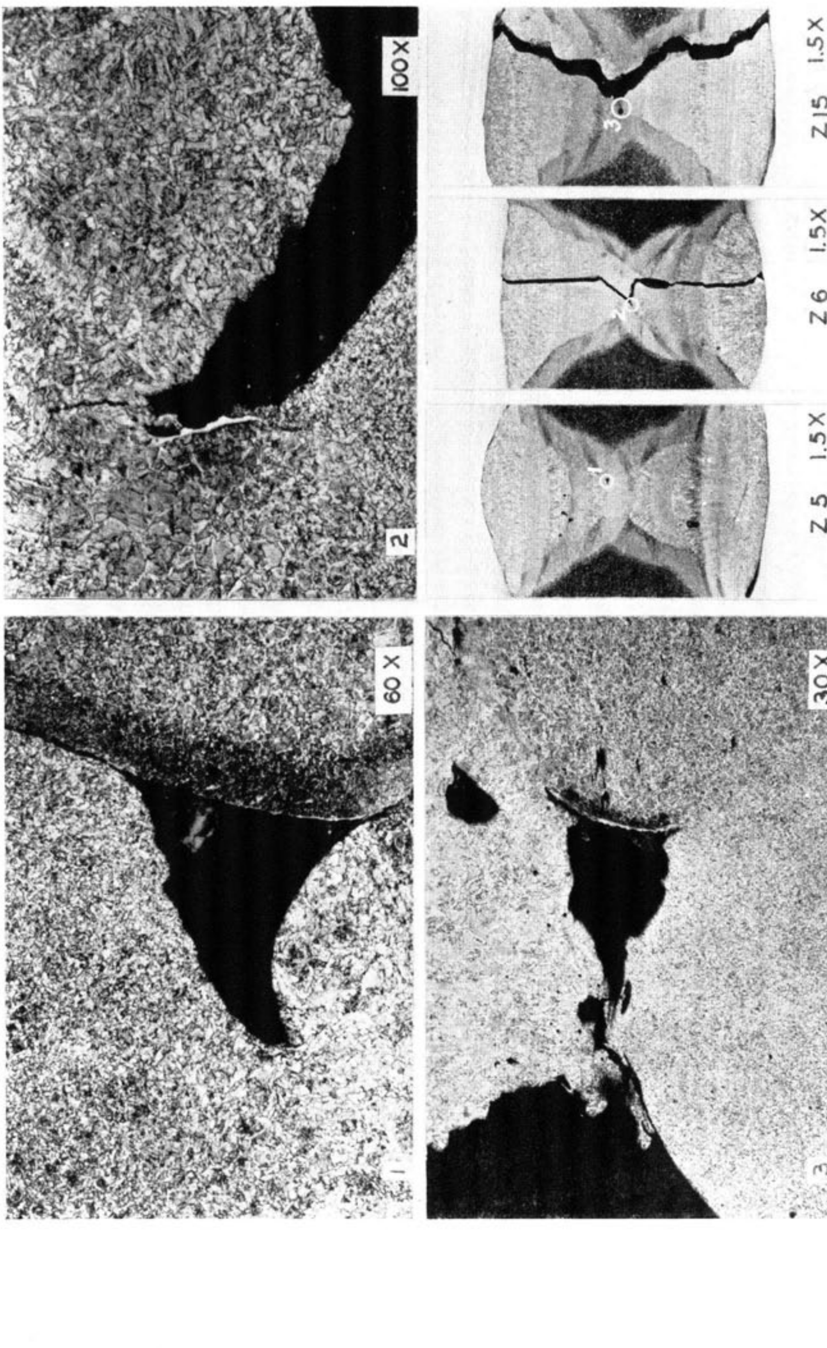


Fig. 31. Micrographs of Unfused Root of Welds in Specimens Z5, Z6, and Z15

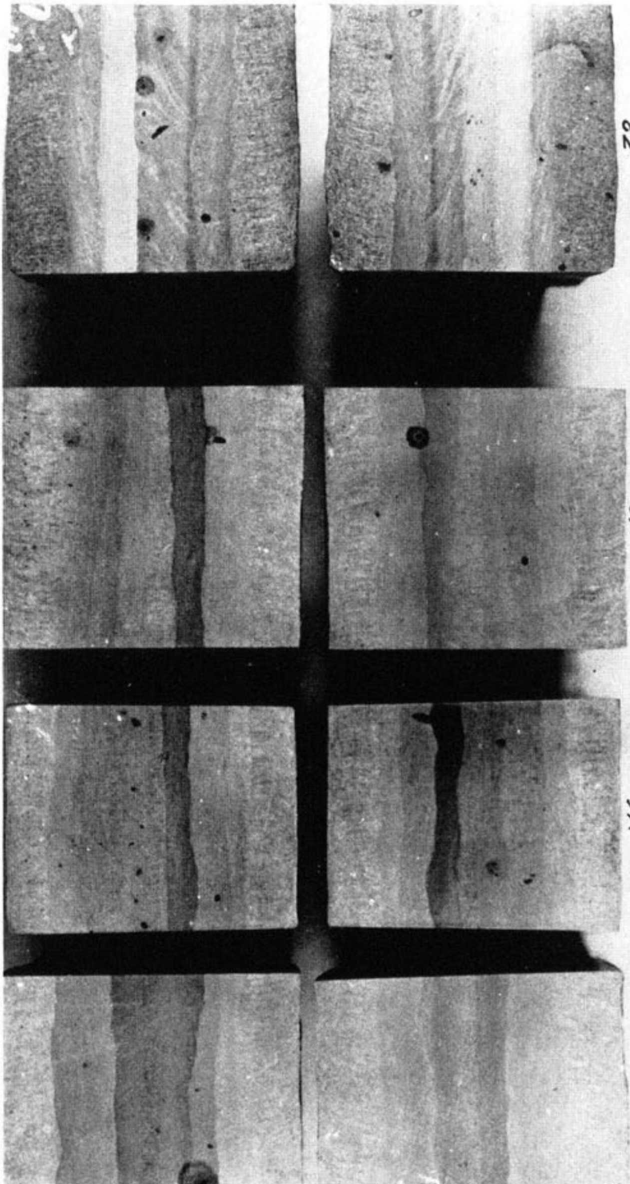


FIG. 32. PHOTOGRAPHS OF SPECIMENS MACRO-ETCHED TO SHOW POROSITY IN WELD METAL

TABLE 12
HYDROGEN CONTENT AND SPECIFIC GRAVITY OF WELD METAL

Specimen No.	Hydrogen, per cent by weight	Specific Gravity
X7	0.00122	7.86
	0.00096	7.81
	Av. 0.00109	7.84
Y1	0.00099	7.85
Y13	0.00101	7.84
	Av. 0.00100	7.85
Z5	0.00047	7.86
	0.00067	7.83
	Av. 0.00057	7.85

from porous areas, which were made easily visible to the unaided eye by a macro-etch on a polished surface with 50-50 HCl-water at 175 deg. F. A few such macro-etched sections of welds are shown in Fig. 32.

It was considered desirable to determine quantitatively the presence of hydrogen in the weld deposits of the X, Y, and Z specimens. Accordingly, samples of weld metal in the form of $\frac{3}{8}$-in. bars about 2 inches long were cut from specimens in which the weld metal had been left fairly intact after the fatigue test. The sample bars of weld metal were so chosen in the X and Z specimens as not to include the unpenetrated root area. The bars were weighed in air and in distilled water to the nearest 0.10 milligram for specific-gravity values before they were sent to the American Rolling Mill Company's laboratory for hydrogen determinations. The hydrogen content and density of the samples are given in Table 12.

The specific gravity was practically the same for all of the specimens tested. This indicated that, aside from lack of root penetration in some of the X and Z specimens, the deposited metal was equally sound in all. The hydrogen content for the Z specimen, however, was only about half of that reported for the X and Y specimens, but the difference was not reflected in the densities obtained. The lower hydrogen content was not, however, effective in decreasing the number of fisheyes found on the fractured surface of the Z specimens. It was not possible to determine from an examination of the sample whether the lower hydrogen content of the Z specimen was due to the welding electrode used or to the method of welding.

A micrographic survey of porosity on polished-and-etched sections of the welds was highly effective in obtaining information as to the microstructure of the porous regions and the form of cracks which start from them. Figures 33, 34, and 35 show porosity typical of several X, Y, and Z specimens, and there was evidence of cracks having originated from the internal stress raiser provided by the pores. The columnar structure of the as-cast weld metal appears to have provided an easy path for the propagation of cracks through the interdendritic area. Porosity occurred both in the columnar and recrystallized areas of the weld deposit. It was found near the root of the weld when the root was well penetrated by the weld deposit. It was frequently found at the junction between two weld deposits as shown in region 2 of Fig. 33, and regions 1 and 3 of Fig. 35.

Micro fissures, such as are shown in Fig. 36, were found quite frequently on some transverse sections of a weld, but in many instances they extended only a short distance normal to the polished surface of the section, and were not visible on a parallel section only 0.02 to 0.05 in. removed from that on which they were found. It is quite possible that these fissures were internal fractures which did not increase in size, due to the release of the fatiguing stress from the area by the development of a major crack in the near vicinity.

The fisheyes, such as are indicated by arrows 1 and 2 in Fig. 37 which were found on the fracture surface of the specimen, consisted of bright circular areas surrounding a central porous area or inclusion. Many of the specimens which fractured through the weld metal, and therefore contained fisheyes, were examined with a binocular microscope at low power. It was found that the center of the fisheye occasionally had a blue-violet inclusion with a highly reflective surface, but generally there was a blowhole with a bright surface and some veins in relief on the internal surface. Many fine cracks, which were judged to be very shallow, were seen on the internal surface of some of the blowholes.

6. *Discussion of Results of Fatigue Tests.—*

Series X

As shown in Table 7, the average fatigue strength for failure at 100 000 cycles was as great for the X as for the basic series and, for failure at 2 000 000 cycles, the average fatigue strength was only slightly less for the former than for the latter. The results, however, are more erratic for the X than for the basic series.

The specimens of the first group in Table 3, X1, X2, and X3, had a high average fatigue strength, but X2 was about 15 per cent stronger than X1 or X3. Specimen X2 broke at the edge of the reinforcement,

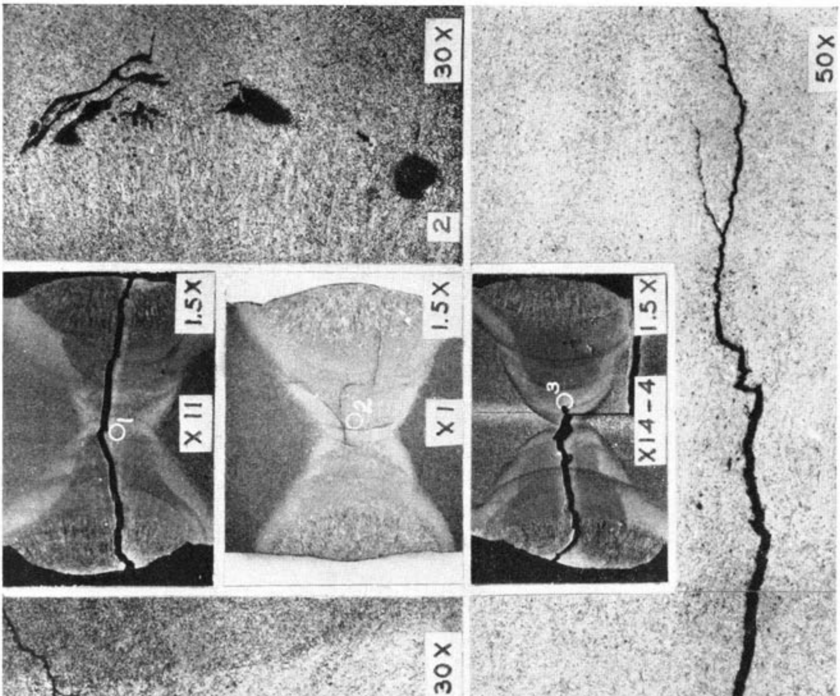


FIG. 33. MICROGRAPHS SHOWING POROSITY AND CRACKS IN X SPECIMENS

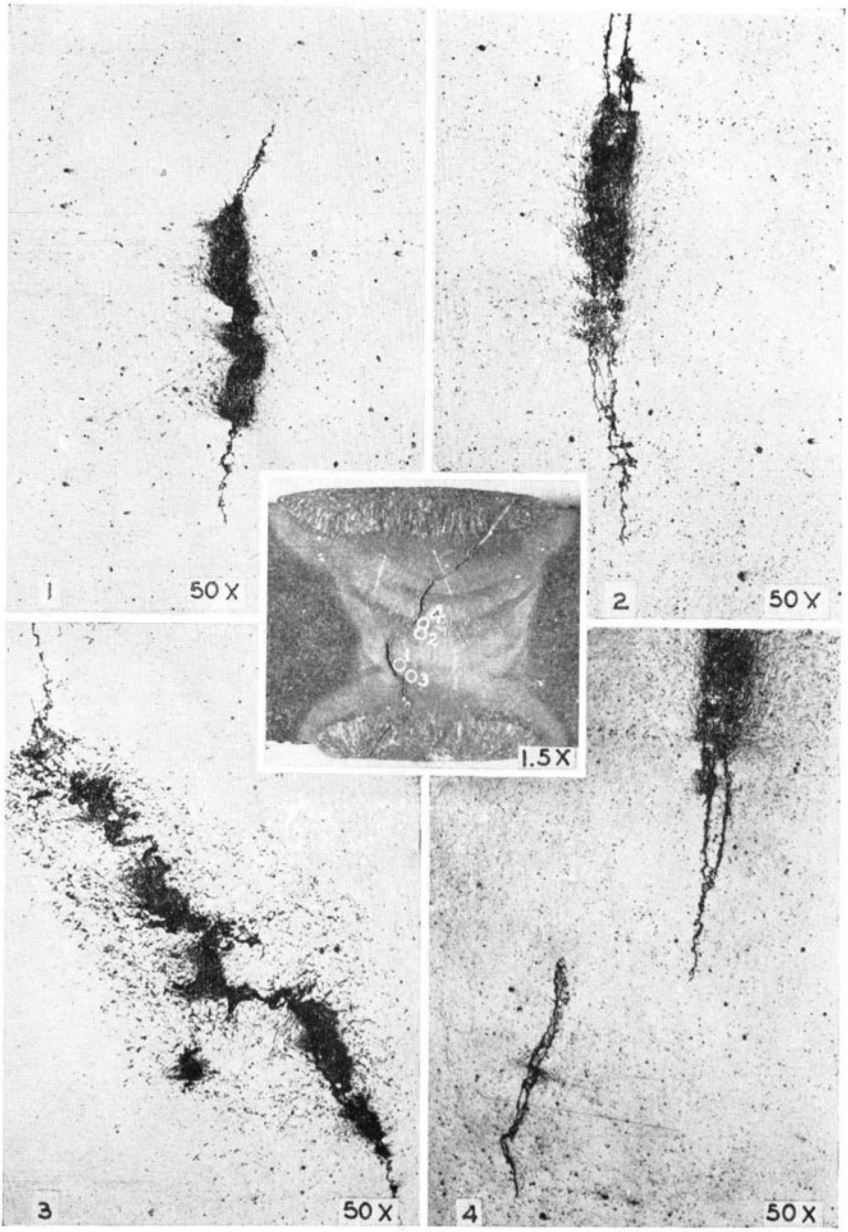


Fig. 34. Micrographs Showing Porosity and Cracks in Y Specimens

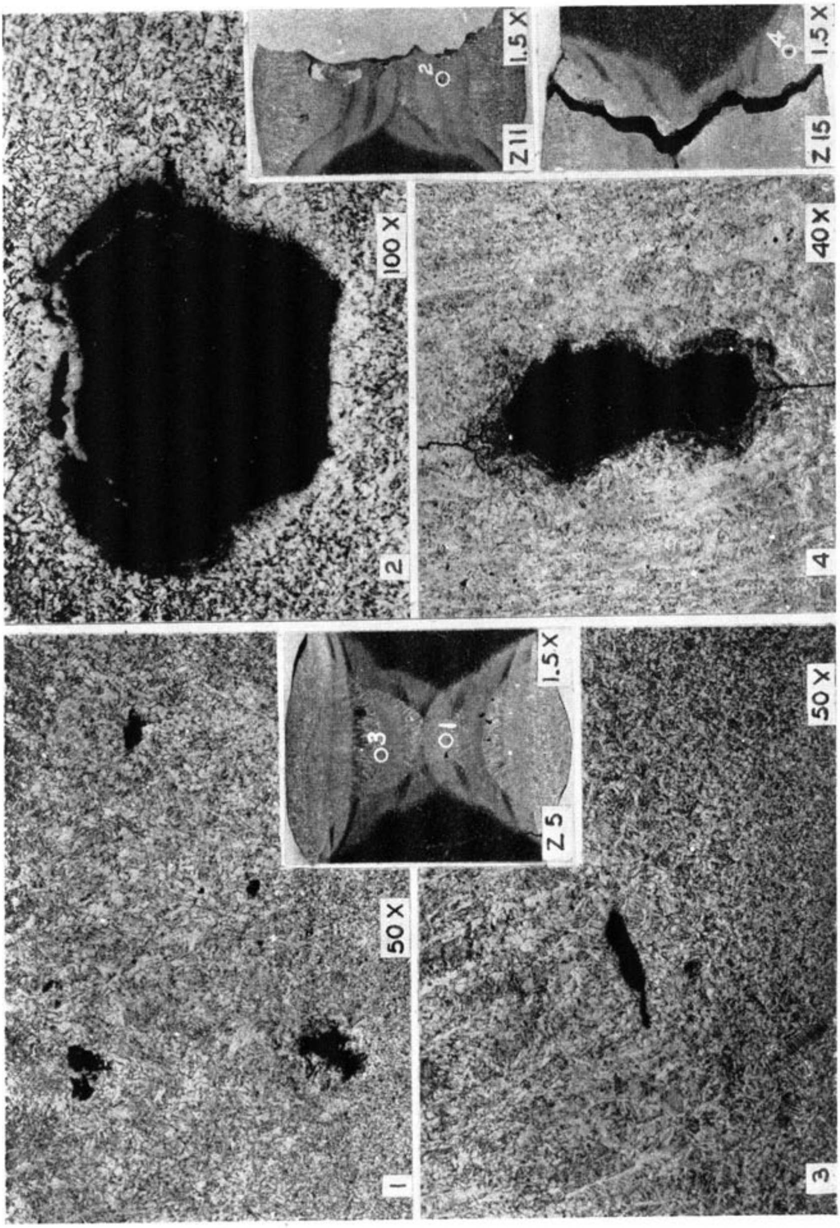


Fig. 35. Micrographs Showing Porosity and Cracks in Z Specimens

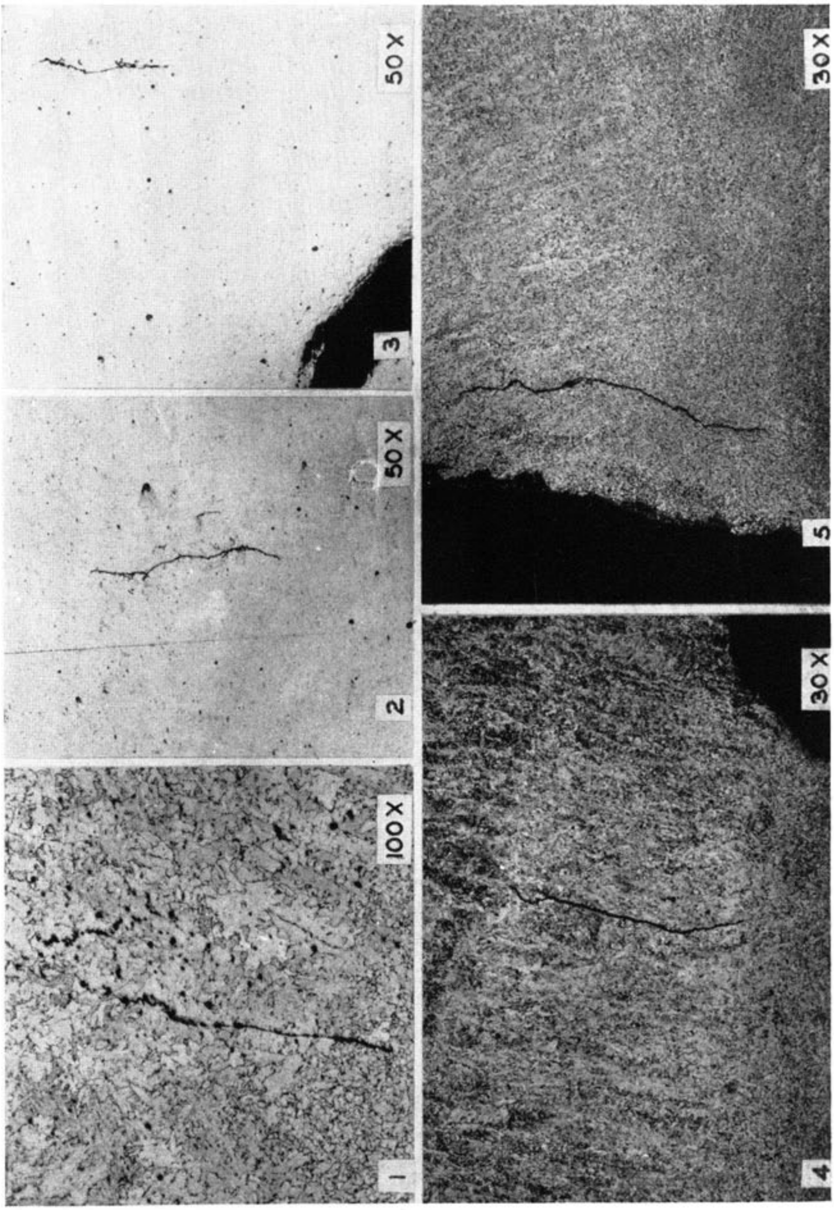


FIG. 36. MICROGRAPHS SHOWING MICRO-FISSURES IN Y SPECIMENS

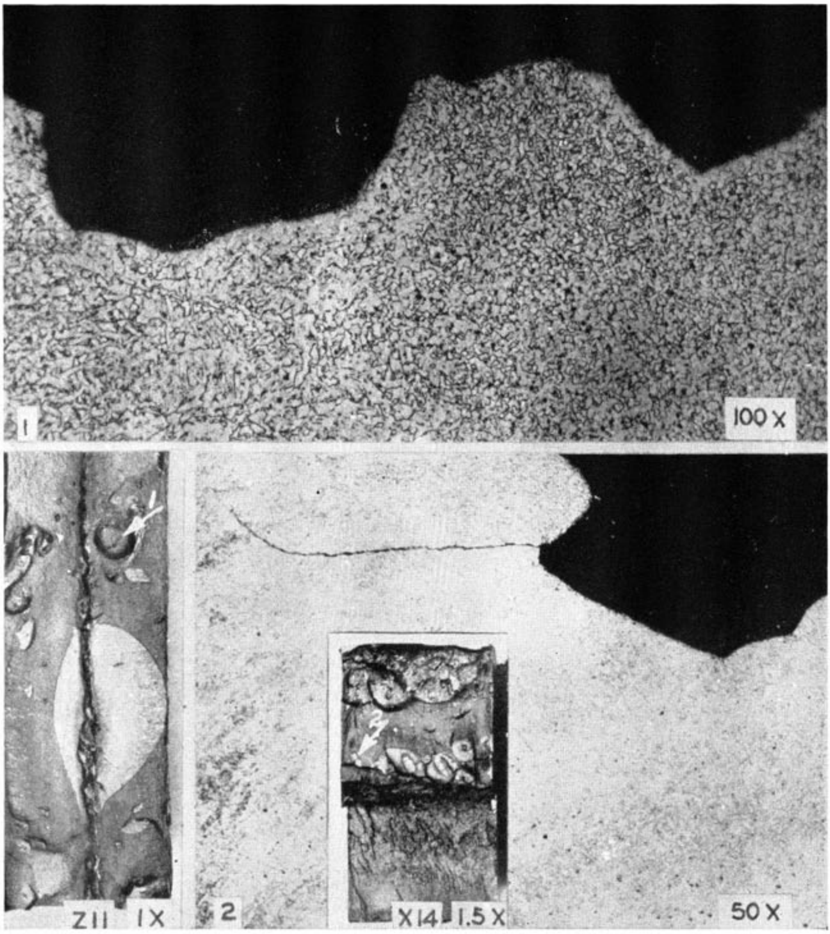


FIG. 37. MICROGRAPHS OF CROSS-SECTION OF FISHEYES IN WELD METAL

whereas X1 and X3 broke through the weld. The appearance of the fracture indicated that failure began at the surface and along the edge of the reinforcement for X2, but that, for X1 and X3, it began at the root of the weld where there was either imperfect fusion or slag inclusion, or both, which acted as a nucleus for the fatigue fracture.

The specimens in the second group of Table 3, X5, X6, and X7, had a high average fatigue strength, but X6 was about 12 per cent stronger than X5 and X7. The fracture of X5 followed the general outline of the surface of contact between the weld and the base metals. Moreover, the surface appearance was that of a separation between two materials rather than a fracture through the crystals of continuous metal, indicating that there had been some lack of fusion. Specimen X6, which was the strongest of the group, failed in the weld, and the fracture showed some minor imperfections at the root, and there was a small particle of slag at the nucleus of the largest fisheye. The third specimen of the group, X7, broke in the base plate several inches from the weld, and at a relatively small number of cycles, so that all that is known about the weld is that its fatigue strength for failure at 100 000 cycles was 20 500 lb. per sq. in. or more. The fracture, Fig. 15, showed some laminations, but there was no well-defined nucleus on the surface of fracture.

The specimens of the third group, X8, X9, X10, and X11, had an average fatigue strength 94 per cent as great as that for the same group of the basic series. The strongest of the group, X9, was 12 per cent stronger than the others. Its fracture began at the surface along the edge of the reinforcement, and there was no nucleus other than the line along the edge where failure began. Specimens X8, X10, and X11 all failed in the weld metal; their fatigue strengths were quite consistent, and each had a fisheye, as shown in Fig. 15, with a slag inclusion as a nucleus.

The specimens in the fourth group of Table 3, X13, X14, and X15, had an average fatigue strength of only 0.87 of that of the corresponding group of the basic series. Moreover, the strongest of the group had only 90 per cent of the average strength of the corresponding group of the basic series. The fracture of X13 had a single large fisheye with a slag inclusion as a nucleus. Moreover, the fracture followed the junction of the weld and base metals for fully half of the section, indicating a lack of fusion. Specimen X14, which was the weakest of the group, broke partly in the weld and partly at the edge of the weld. The base plate was laminated at mid-thickness, a defect that caused the unusual fracture shown in Fig. 11. The fracture of X15, shown in Fig. 19, indicated imperfect fusion and some slag inclusions at the root of the weld.

The fracture of many of the X specimens showed a columnar structure at the surface of the weld for a depth of at least $\frac{3}{16}$ in. This resulted from the fact that the last layer was quite thick, as shown in Fig. 2. The columnar structure extended well below the surface of the base metal, as shown in Fig. 11, and may have affected the fatigue strength of the weld somewhat but there is no direct evidence to indicate that this was true.

The welds of all specimens were inspected by x-ray and all radio-

TABLE 13
CORRELATION BETWEEN RADIOGRAPH RATING AND FATIGUE-STRENGTH RATING
X Series

Specimen No.	Radiograph Rating	Fatigue-Strength Rating
X1	D	1.01
X2	D	1.14
X3	E	0.99
X5	D	0.96
X6	C	1.06
X7	C	0.92
X8	C	0.92
X9	C	1.02
X10	C	0.92
X11	C	0.87
X13	C	0.90
X14	E	0.83
X15	D	0.90

graphs showed considerable porosity. The radiograph rating and the fatigue-strength rating are compared in Table 13. The fatigue-strength rating of a specimen as here used is the ratio of the fatigue strength of that specimen to the average fatigue strength of the corresponding group of the basis series. The data in Table 13 show no correlation between the radiograph rating and the fatigue-strength rating. This does not necessarily mean that flaws shown by radiographs are not injurious but rather that the stress-raising effect of lack of fusion and of the change in section at the edge of the reinforcing were more injurious than the flaws shown by the radiograph.

The smallest value of the fatigue-strength rating for the X series was 0.83.

Series Y

As shown in Table 7, the average fatigue strength of the Y specimens was about 96 per cent of the average fatigue strength of the basic series for all groups. Moreover, with the exception of Y6 and Y13, Table 4, the results of the tests were very consistent. Specimens Y6 and Y13 were the only ones that broke through the weld. The fracture of Y6, Fig. 16, showed a large fisheye with a well-defined nucleus, but the character of the nucleus was uncertain. It appeared to have been some kind of inclusion. The fracture of Y13, the other weak specimen, showed some fisheyes near the root of the weld.

The fracture of Y10, shown in Fig. 16, was typical of the fractures of Y9, Y11, and Y15, all of which broke along the edge of the reinforcement. (The dark area is the fatigue fracture.) The fractures of

Y7 and Y12, both of which broke along the edge of the reinforcement, had a woody appearance, indicating slight laminations, and Y1, Y2, Y5, and Y14 showed some, but even less definite, indications of lamination. The fracture of Y3 is unusual, and might be considered as indicating laminations, but the fatigue strength was slightly greater than the average fatigue strength of the corresponding basic series. There was no significant difference in the fatigue strength between the specimens that were laminated and those that were not laminated.

All of the Y specimens were inspected by x-ray and none of the radiographs showed anything more than a mere trace of porosity.

The low fatigue strength of Y6 and Y13 would seem to have been due to a weakness at the root of the weld. This weakness was probably due to an inclusion which acted as a stress raiser for Y6, and may have been due to a lack of fusion for Y13.

The smallest value of the ratio minimum-to-average stress for the Y series, which occurred for Y13, was 0.83. This is the same as the corresponding ratio for X14, the weakest of the X specimens.

Series Z

The average fatigue strength of the Z series, given in Table 7, was about 92 per cent of the average fatigue strength of the corresponding groups of the basic series but individual tests were very erratic for some groups. The specimens of the first group, Z1, Z2, and Z3, all broke in the weld, and the values of the fatigue strength were quite uniform but about 7 per cent lower than the average fatigue strength of the same group of the basic series. The fractures, shown in Fig. 17, were very similar, each having a large fisheye and each showing evidence of slag inclusion and imperfect fusion at the root of the weld. The specimens of the second group, Z5, Z6, and Z7, all broke in the weld. The fatigue strength was considerably lower for Z5 and Z7 than for the basic series and was only 84 per cent as great for Z6 as for Z5 and Z7. The fracture of Z6, shown in Fig. 17, shows much the same flaws as for Z1, Z2, and Z3, and in addition there was an indication of a lack of fusion. Of the third group of specimens, Z8, Z9, Z10 and Z11, Z9 and Z10 were appreciably stronger than the corresponding basic series, but Z8 and Z11 were very much weaker. The fracture of Z9 began at the surface along the edge of the reinforcement, and was entirely in the base metal, as shown in the figure; the fracture for Z10 was several inches from the weld. The fracture was in the weld metal for both Z8 and Z11. There were indications of slag inclusion

TABLE 14
CORRELATION BETWEEN RADIOGRAPH RATING AND FATIGUE-STRENGTH RATING
Z Series

Specimen No.	Radiograph Rating	Fatigue-Strength Rating
Z1	C	0.93
Z2	D	0.94
Z3	D	0.92
Z5	E	0.93
Z6	D	0.80
Z7	E	0.98
Z8	D	0.81
Z9	D	1.02
Z10	D	1.11
Z11	E	0.81
Z12	D	0.95
Z13	D	1.08
Z14	D	0.85
Z15	D	0.73

and incomplete fusing at the root of the weld for both specimens. The fracture for Z11 followed the junction of the weld metal and base metal, indicating lack of fusion. The tests of the fourth group, Z12, Z13, Z14, and Z15, also were very erratic, Z13 being stronger than the basic series, and Z12 nearly as strong, whereas Z14 and Z15 were both much weaker. The usual relation between the character of the fracture and the fatigue strength was reversed for this group, Z12 and Z13 had the characteristic fracture through the root of the weld, but had a high fatigue strength, whereas, Z14 broke at the edge of the reinforcement, but at a relatively low number of cycles. The strength of Z15, which broke through the root of the weld, was low as would be expected from the fracture.

Radiograph ratings were made of all specimens, and the correlation between the radiograph rating and the fatigue-strength rating is given in Table 14. It would seem from this table that there was no consistent relation between the radiograph rating and the fatigue strength of the specimen.

The smallest value of the fatigue-strength rating, which occurred in the case of Z15, was 0.73, a value considerably lower than the corresponding values for the X and Y series.

7. *Summary.*—Hardness values for representative X, Y, and Z specimens indicate that hardening of the base metal in the heat-affected zone was not excessive. The maximum hardness range, minimum in unaffected base metal to maximum in heat-affected zone, had

values of 93, 83, and 80 for the X, Y, and Z series, respectively. The hardness maxima were 217, 224, and 202 for the heat-affected zone, and 183, 158, and 196 for the weld metal, respectively, for the same series.

The radiographs showed small amounts of porosity in the X and Z specimens, but showed only a trace in the Y specimens. The lack of fusion and slag inclusions, faults that seriously affect the fatigue strength of the welds, were apparent in the radiographs of the X and Z series but were not apparent in the Y series.

The relative fatigue strengths of the X, Y, Z, and basic series are compared in Table 7.

For the X series, the ratio of average values of the fatigue strength for failure at 100 000 cycles was approximately unity for both cycles (0 to tension and tension to an equal compression), and the lowest value of the ratio minimum-to-average values was 0.92. For failure at 2 000 000 cycles, the ratio of the average values of the fatigue strength had values of 0.94 and 0.88 for cycles in which the stress varied from zero to tension and from tension to an equal compression, respectively. The ratio minimum-to-average values was 0.87 and 0.83, respectively, for the same stress cycles.

For the Y series, the ratio of average values of the fatigue strength was about 0.96 for all groups. For failure at 100 000 cycles, the ratio minimum-to-average values was 0.92 and 0.88 for cycles in which the stress varied from zero to tension and from tension to an equal compression, respectively. For failure at 2 000 000 cycles, the corresponding ratios were 0.95 and 0.83, respectively.

For the Z series, the ratio of average values of the fatigue strength was about 0.92 for all groups. For failure at 100 000 cycles, the ratio minimum-to-average values was 0.92 and 0.80 for cycles in which the stress varied from zero to tension and from tension to an equal compression, respectively. For failure at 2 000 000 cycles, the corresponding ratios were 0.81 and 0.73, respectively.

With a few exceptions, specimens that broke in the base metal at the edge of the reinforcement had a high fatigue strength, whereas those that failed through the weld metal had a low fatigue strength. The low fatigue strength of specimens that broke in the weld was attributed to slag inclusions and lack of penetration at the root of the weld and, in a few instances, to a lack of fusion of the base metal.

III. Specimens Welded in Flat Position
Series XX, P, and R; Group 2

8. *Description of Specimens.*—Because of the relatively low fatigue strength of some specimens of the X, Y, and Z series, it seemed desirable to test additional commercial butt welds in ⅞-in. carbon-steel plates. The specimens for the three new series, designated as XX, P, and R, were welded in separate commercial fabricating shops, but the plates for all specimens, furnished by the Fatigue Committee, were from the same heat. Fabricator XX was the same as X and fabricator P was the same as Z. Because the plates of series X contained laminations, all plates for the XX, P, R, and subsequent series were examined for laminations before being accepted. This examination, made by a commercial inspection bureau employed by the Fatigue Committee, was as follows: The oxy-acetylene flame was kept under constant observation while the plates were cut with a torch. Edges on which laminations were found were machined off ⅛ in. and again examined. In each instance the lamination showed on the machined surface. The plates were also examined for surface flaws. The inspector's report indicated that the plates were as free of laminations and surface flaws as can be expected of commercial steel.

The tests of Groups 3, 4, 5, and 6, described in Chapters IV, V, VI, and VII, were planned at the same time as the tests of Group 2 with the idea of comparing the results of the tests of the various series. For this reason, enough plates were obtained from one heat, and subjected to the inspection just described, to provide for all specimens of all groups. The tensile properties and the chemical composition of the plate material, determined from specimens cut from the same parent plates as the fatigue specimens, are given in Tables 15 and 16, respectively.

The welding was done by qualified welders working under an inspector from a commercial inspection bureau employed by the Fatigue Committee. All welding was done in the flat position and was specified to be done in accordance with the American Welding Society's 1939 Specifications for Welded Highway and Railway Bridges, but each fabricator was allowed to use his own type of weld and welding procedure and to select his own electrode. The details of the welding procedure, as furnished by the inspector, are given in Fig. 38. The dimensions of the specimens were the same as for the X, Y, Z, and basic series, given in Fig. 1.

In order to facilitate a comparison of the results of these tests with

TABLE 15
PHYSICAL PROPERTIES OF PLATE MATERIAL
Groups 2, 3, 4, 5, and 6

Specimen No.	Yield Point, lb. per sq. in.	Ultimate Strength, lb. per sq. in.	Elongation in 8 in., per cent	Reduction of Area, per cent
A2	34 100	63 600	31.0	55.1
A8	31 750	61 600	30.9	57.1
	Av. 32 930	62 600	31.0	56.1
B2	34 750	64 200	30.0	49.8
B8	33 700	63 700	30.7	54.3
	Av. 34 230	63 950	30.4	52.1
C2	35 000	63 800	30.0	54.1
C8	34 500	63 800	28.4	54.6
	Av. 34 750	63 800	29.2	54.4
D2	33 600	62 400	29.0	56.5
D8	34 600	63 800	29.8	55.5
	Av. 34 100	63 100	29.4	55.0
E3	29 600	62 100	30.0	55.8
E8	32 000	62 200	30.3	54.2
	Av. 30 800	62 150	30.2	55.0
G2	35 400	64 750	32.6	55.1
G8	34 950	63 100	31.3	55.8
	Av. 35 180	63 930	32.0	55.5
P15	31 500	62 900	29.8	55.5
R2	34 500	66 200	27.7	50.9
R9	32 800	64 000	29.7	53.7
R13	32 500	63 200	30.9	56.1
	Av. 33 270	64 470	29.5	53.6

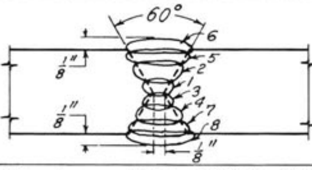
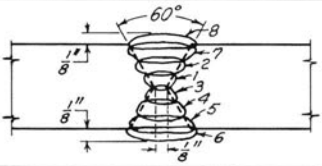
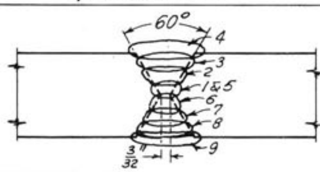
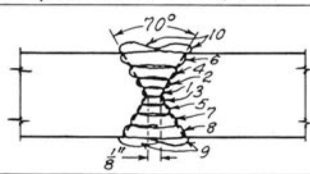
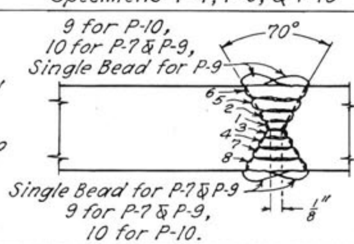
TABLE 16
CHEMICAL COMPOSITION OF PLATE MATERIAL
Groups 2, 3, 4, 5 and 6
XX, P, R, A, B, C, D, E, F, G, S, T, and U Series*

Series	Chemical Content, per cent				
	C	Mn	Si	P	S
A	0.255	0.529	0.007	0.009	0.032
P	0.262	0.550	0.007	0.010	0.034
R	0.255	0.535	0.006	0.010	0.035

*The plates for the specimens for all of these series were from the same heat.

the results from tests of the X, Y, Z, and basic series, the XX, P, and R series were tested, in general, on the same cycle as had been used for the previous series. The results of the tests are given in Section 9.

9. *Results of Tests.*—The results of the individual tests are given in Tables 17 to 19, and a summary of the results is given in Table 20.

Weld		Pass No.	Elect. Size	Current, Amperes
Specimens XX-1 to XX-3 & XX-7 to XX-15				
A.W.S. E-6012 D.C. Reversed Polarity. All passes in same direction.		1,3 2,4,5,6,7,8	5/32" 3/16"	175 225
Specimens XX-4, XX-5 & XX-6				
A.W.S. E-6012 D.C. Reversed Polarity. All passes in same direction.		1,3 2,4,5,6,7,8	5/32" 3/16"	175 225
Specimens R				
A.W.S. E-6030 A.C. 25 Cycles Type B Electrodes		1,5 2,3,4 6,7,8,9	5/32" 3/16" 3/16"	150 240 250
Specimens P-6 & P-8*				
A.W.S. E-6010 D.C. Reversed Polarity Alternate passes to right and left for succeeding passes after first one.		All	3/16	160-180
Specimens P-7, P-9, & P-10*				
A.W.S. E-6010 D.C. Reversed Polarity Alternate passes to right and left for succeeding passes after first one.		All	3/16"	160-180

*Three fatigue specimens each were cut from P-6, P-7, P-8, P-9, and P-10

Fig. 38. Details of Welds. XX, P, and R Series

TABLE 17

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION

XX Series

Specimen No.	Cycle	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Crack*
				$n =$ 100 000	$n =$ 2 000 000	
XX4	0 to Tens.	0 to 30.0	246.7	33.7		1
XX6	0 to Tens.	0 to 30.0	285.7	34.4		1, 2
XX14	0 to Tens.	0 to 30.0	226.6	33.4		1, 2
Av.				33.8		
XX1	0 to Tens.	0 to 25.0	984.4		22.8	1
XX7	0 to Tens.	0 to 25.0	1103.2		23.2	2
XX9	0 to Tens.	0 to 25.0	1154.9		23.3	2
Av.					23.1	
XX5	Comp. Rev.	+20.0 to −20.0	402.7	24.0		1, 2
XX10	Comp. Rev.	+20.0 to −20.0	279.5	22.9		1, 2
XX11	Comp. Rev.	+20.0 to −20.0	391.5	23.9		2
XX8	Comp. Rev.	+19.1 to −19.1	429.1	23.1		1, 2
Av.				23.5		
XX2	Comp. Rev.	+16.0 to −16.0	336.8		12.7	1, 2
XX15	Comp. Rev.	+16.0 to −16.0	263.0		12.3	2
XX12	Comp. Rev.	+16.0 to −16.0	545.5		13.5	1
Av.					12.8	

*See Fig. 4.

TABLE 18

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION

P Series

Specimen No.	Cycle	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Crack*
				$n =$ 100 000	$n =$ 2 000 000	
P10	0 to Tens.	0 to 30.0	209.5	33.0		1
P1	0 to Tens.	0 to 30.0	324.7	35.0		2
P2	0 to Tens.	0 to 30.0	277.8	34.3		2
Av.				34.1		
P13	0 to Tens.	0 to 25.0	507.8		20.9	2
P3	0 to Tens.	0 to 25.0	986.1		22.8	2
P14	0 to Tens.	0 to 25.0	391.8		20.2	2
Av.					21.3	
P4	Comp. Rev.	+20.0 to −20.0	67.2	19.0		1, 2
P5	Comp. Rev.	+20.0 to −20.0	78.2	19.4		2
P15	Comp. Rev.	+20.0 to −20.0	42.3	17.9		2
Av.				18.8		
P7	Comp. Rev.	+16.0 to −16.0	118.0		11.1	1, 2
P9	Comp. Rev.	+16.0 to −16.0	305.1		12.5	1
P11	Comp. Rev.	+16.0 to −16.0	197.0		11.8	1, 2
Av.					11.8	

*See Fig. 4.

TABLE 19

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION

R Series

Specimen No.	Cycle	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength in 1000's of lb. per sq. in. n = 100 000	Fatigue Strength in 1000's of lb. per sq. in. n = 2 000 000	Location of Fatigue Crack*
R10	0 to Tens.	0 to 30.0	485.5	36.8		1
R14	0 to Tens.	0 to 30.0	359.4	35.4		1
R2	0 to Tens.	0 to 30.0	181.2	32.4		2
Av.				34.9		
R3	0 to Tens.	0 to 25.0	1405.1		23.9	1, 2
R6	0 to Tens.	0 to 25.0	105.7		17.1	1
R7	0 to Tens.	0 to 25.0	1300.8		23.6	2
R10	0 to Tens.	0 to 25.0	1471.0		24.0	2
Av.					22.2	
R9	Comp. Rev.	+20.0 to −20.0	434.7	24.2		1, 2
R11	Comp. Rev.	+20.0 to −20.0	83.9	19.6		1, 2
R13	Comp. Rev.	+20.0 to −20.0	148.6	21.1		1, 2
Av.				21.6		
R1	Comp. Rev.	+16.0 to −16.0	83.4		10.6	1
R4	Comp. Rev.	+16.0 to −16.0	935.9		14.5	4
R5	Comp. Rev.	+16.0 to −16.0	85.6		10.6	1
R8	Comp. Rev.	+16.0 to −16.0	148.2		11.4	1
Av.					11.8	

*See Fig. 4.

TABLE 20

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES IN AS-WELDED CONDITION

XX, P, and R Series; Summary of Results

Stress Cycle	Fatigue Strength, lb. per sq. in. n = 100 000				Fatigue Strength, lb. per sq. in. n = 2 000 000			
	Basic Series	XX Series	P Series	R Series	Basic Series	XX Series	P Series	R Series
				Average Values				
Zero to tension	33 100 1.00	33 800 1.02	34 100 1.03	34 900 1.05	22 500 1.00	23 100 1.03	21 300 0.95	22 200 0.99
Tension to equal compression	22 300 1.00	23 500 1.05	18 800 0.84	21 600 0.97	14 400 1.00	12 800 0.89	11 800 0.82	11 800 0.82
				Minimum Values				
Zero to tension	32 000 0.97	33 400 1.01	33 000 1.00	32 400 0.98	22 100 0.98	22 800 1.01	20 200 0.90	17 100 0.76
Tension to equal compression	21 400 0.96	22 900 1.03	17 900 0.80	19 600 0.88	13 300 0.92	12 300 0.85	11 100 0.77	10 600 0.74

The upper line gives the fatigue strength, the lower line gives the ratio of the fatigue strength to the corresponding average fatigue strength of the basic series.

Each average is the average of either three or four tests, and each minimum is the minimum of the group.

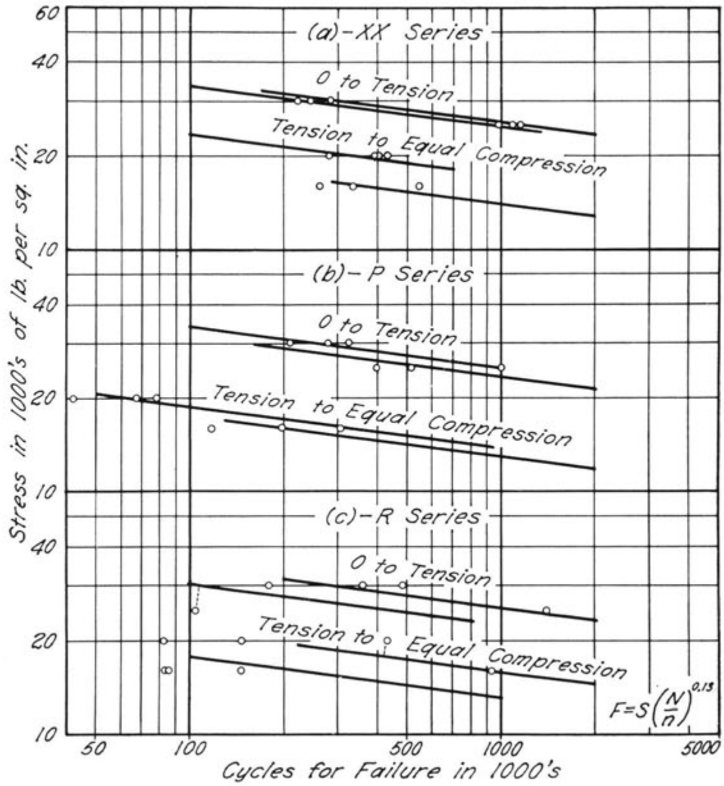


FIG. 39. S–N DIAGRAMS FOR COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES. XX, P, AND R SERIES

Corresponding data for the basic series are given in Table 6. All specimens were tested in the as-welded condition.

The *S-N* diagrams, Fig. 39, were drawn in the same manner as for the X, Y, and Z series, described in Section 4. The *S-N* diagram for the XX series, cycle zero to tension, represents the results of the tests very well, but for the cycle, tension to an equal compression, the average number of cycles for failure was no greater for a stress of 16 000 lb. per sq. in. than for a stress of 20 000 lb. per sq. in. The specimens tested at the higher stress had a fatigue strength greater than the basic series and those tested at the lower stress had a fatigue strength less than the basic series. The *S-N* diagrams for the P series represent the data fairly well, but for the R series the number of cycles for failure was no greater at the lower stresses than at the higher

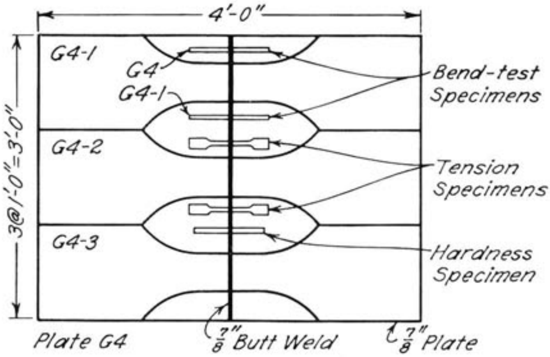


FIG. 40. LOCATION OF FATIGUE SPECIMENS AND STATIC SPECIMENS IN PARENT PLATE

stresses. Moreover, tests at the same stress gave widely differing results. For example, R3 and R6 were both tested on a cycle for which the stress varied from zero to a tension of 25 000 lb. per sq. in. Although R3 withstood 1 405 100 cycles, R6 broke at 105 700 cycles. Likewise, R9 and R11 were both tested on a cycle for which the stress varied from 20 000 lb. per sq. in. tension to an equal compression, but R9 broke at 434 700 and R11 at 83 900 cycles. Also R1 and R4 were both tested on a cycle for which the stress varied from 16 000 lb. per sq. in. tension to an equal compression, but R1 broke at 83 400 and R4 at 935 900 cycles.

The results of the XX, P, and R series, summarized in Table 20, are discussed in Section 12.

10. *Metallurgical Studies.*—Metallurgical studies were made of the XX, P, and R specimens similar to those made on the X, Y, and Z specimens described in Section 5. The XX and P specimens were found to have major laminations in the base plate, those in the XX specimens being considerably more pronounced than the ones in the P specimens. The R specimens appeared to be entirely free from major laminations. The inspector reported that the parent plates from which specimens XX1, XX2, XX3, and R15 were cut contained minor laminations, but that the parent plates from which the other XX, P, and R specimens were cut were free from laminations. Apparently a repeated or reversed stress will open laminations that cannot be detected in an unstressed plate by the usual inspection methods.

Studies of the unaffected base metal, the weld metal and the heat-affected base metal of specimens XX, P, and R indicated that the

TABLE 21
VICKERS HARDNESS NUMBERS FOR BASE AND WELD METAL
XX, P, and R Series

Specimen Series	Hardness Series No.	Unaffected Base Metal			Heat-Affected Zone		Weld Metal		
		Minimum	Maximum	Average	Minimum	Maximum	Minimum	Maximum	Average
XX	1	130	145	140	152	181	161	170	167
	2	145	165	152	168	195	176	181	180
	3	137	151	144	150	179	166	184	172
P	1	122	150	135	166	211	152	169	160
	2	123	167	135	167	189	127	152	145
	3	122	145	132	145	216	154	179	160
R	1	142	157	145	151	179	158	164	162
	2	134	160	142	141	182	131	158	144
	3	142	152	145	148	186	151	162	158

microstructures of these specimens were similar to those found in the X and Z specimens, reported in Section 5.

Hardness Measurements

Hardness tests, similar to those described for the X, Y, and Z specimens, were made on unstressed control specimens cut from between the fatigue specimens, as shown in Fig. 40. The hardness data are given in Table 21 and are shown graphically by the diagrams of Fig. 41. The hardness of the unaffected base metal and of the heat-affected base metal was approximately the same for the XX, P, and R specimens as it was for the X, Y, and Z specimens; the hardness of the weld metal for the XX, P, and R series was about the same as for the Y specimens, but was somewhat lower than for the X and Z specimens.

There was a considerable increase in base-metal hardness of the P specimen close to the heat-affected zone, similar to that noted especially for the Z specimens. Since the hardness tests were carried out on specimens XX, P, and R welds which had not been tested in fatigue, it would seem that the increase in hardness of the unaffected base metal near the heat-affected zone was due to sub-critical aging. There is no evidence that this aging had any appreciable effect upon the fatigue strength of the specimen.

Fatigue Fractures

A classification of the fatigue failures on the basis of their location is given in Table 22. Most of the XX specimens failed at the edge of the weld, but for six specimens the failure at the edge of the weld was

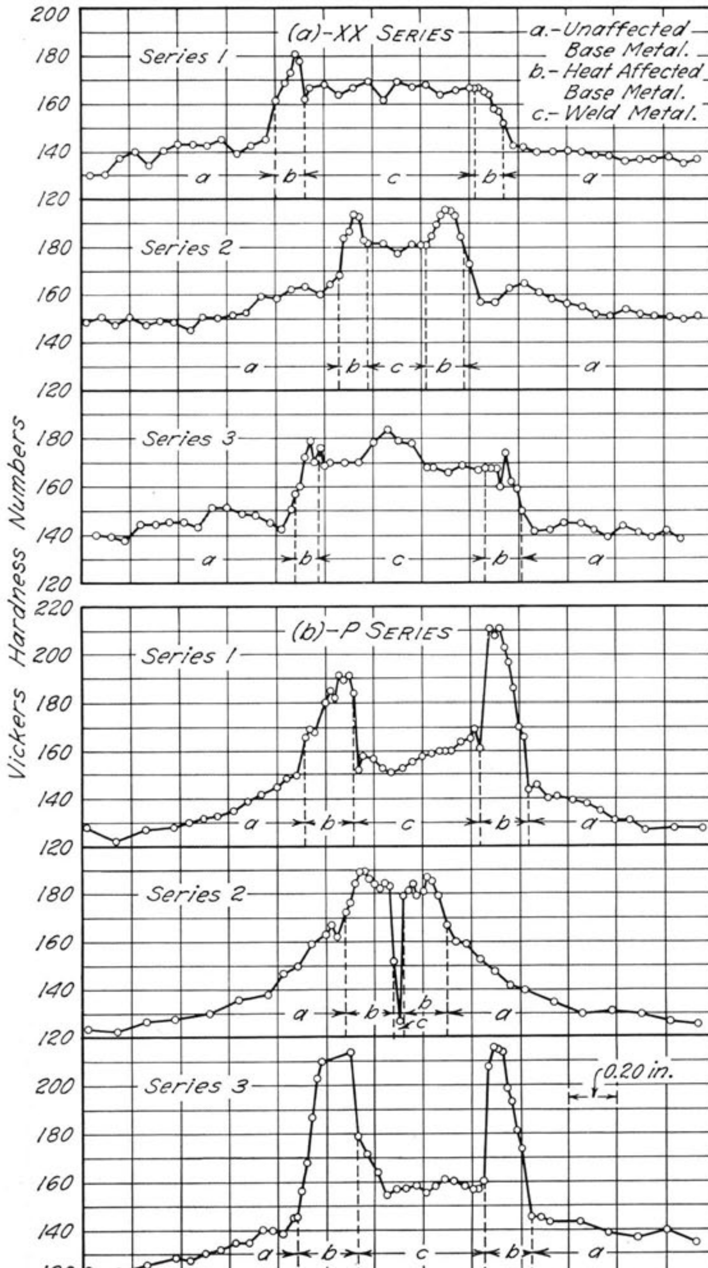


Fig. 41. Hardness Diagrams for Commercial Butt Welds

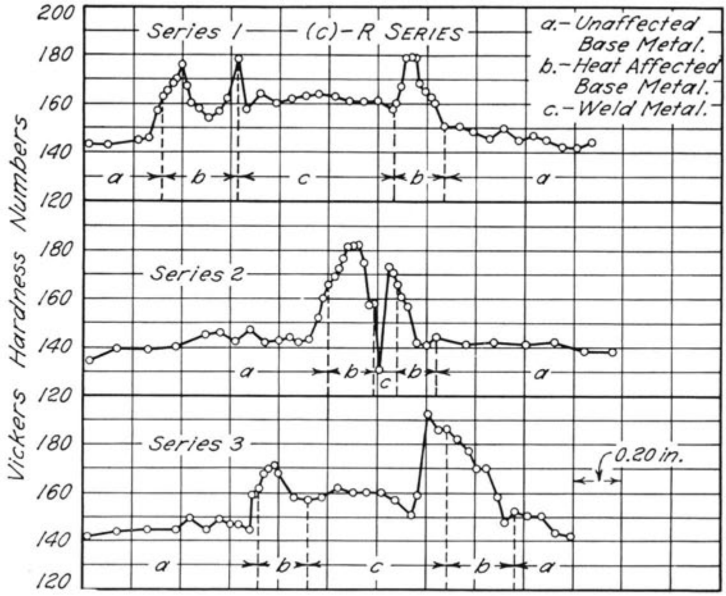


FIG. 41 (CONCLUDED). HARDNESS DIAGRAMS FOR COMMERCIAL BUTT WELDS

TABLE 22
CLASSIFICATION OF FATIGUE FRACTURES
XX, P, and R Series

Series	Number of Failures at Edge of Weld	Number of Failures Through Weld	Number of Failures Partly in Weld and Partly at Edge of Weld	Number of Failures in Plate
XX	4	3	6	0
P	7	2	3	0
R	3	6	4	1

combined with failure through the weld. The separate fractures of the latter type were joined by a major lamination at approximately mid-thickness of the specimen. The fracture of specimen X14, for which the macrograph X14-4 is shown in Fig. 18, is typical of the fractures in many of the XX specimens. Most of the P specimens failed at the edge of the weld.

The fracture for P7 was in the weld on one side of the specimen and at the edge of the weld on the other side, as shown in Fig. 42. Two overlapping beads were used in making the weld, as shown at the right of the figure. The path of that portion of the fracture in the weld metal may have been determined by the external stress raiser resulting from the junction of the two beads in combination with the internal stress raiser due to a lack of penetration at the root of the weld, two features that seem to be detrimental. It is of interest to note that P7 was among the weakest of the butt-weld specimens that were tested.

The fractures of the R specimens were mostly either in the weld, or partly in the weld and partly at the edge of the weld, and were similar to the fractures of the Z specimens described in Section 5. The lack of root penetration generally present in both Z and R specimens acted as internal stress raisers that were more severe than the change in section at the edge of the reinforcement, and caused failure to occur in the weld metal.

A survey of the porosity in the weld metal of the XX, P, and R specimens was made by sectioning many specimens of each series and etching the polished section in boiling 50-50 HCl and water. The sections were taken longitudinally through the middle of the weld (transverse to the specimen), and disclosed the porosity at the root of the weld and in the center of the outer beads. In general, the XX specimens had a large number of small blowholes distributed throughout the weld deposit, with a slightly greater number at the root of the weld than in the outer beads. For the P specimens, the blowholes appeared to be most prevalent at the root on one side of the double V; the remainder of the weld was quite free from this defect. The R specimens were remarkably free from blowholes, but some of the etched sections disclosed long streaks of slag indicative of a lack of fusion due to a slag coating on the scarf.

The density of samples of weld metal for the XX, P, and R specimens was determined by the method described in Section 5 for the X, Y, and Z specimens. The average specific gravities determined by weighing in air and in distilled water were 7.83, 7.86, and 7.87, respectively, for the weld deposit of XX, P, and R specimens. It is of interest to note that the specific gravity was least for the XX specimens, the ones having a large number of small voids distributed throughout the weld metal.

11. *Static Tests.*—The fatigue specimens were cut from a parent plate containing a continuous weld, as shown in Fig. 40. Static tension and side-bend specimens were machined from the piece cut from between two adjacent fatigue specimens. Adjacent side-bend and fatigue specimens have the same number. If a side-bend test is taken from each side of a fatigue specimen, they both have the same number

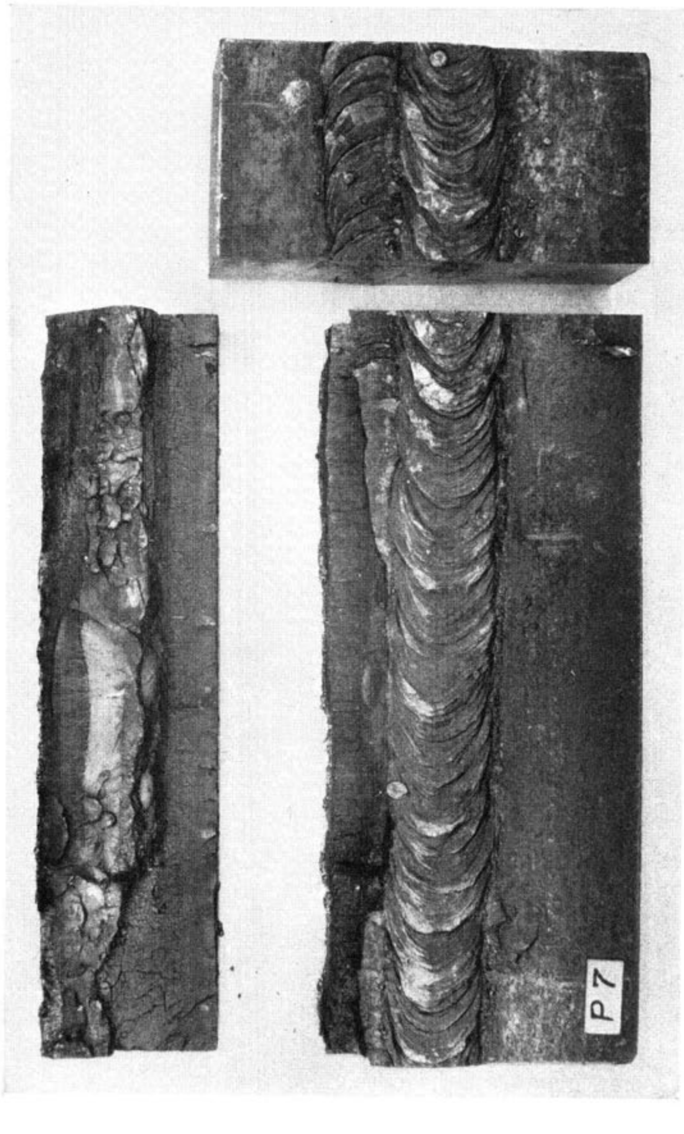


FIG. 42. FRACTURE OF SPECIMEN P7

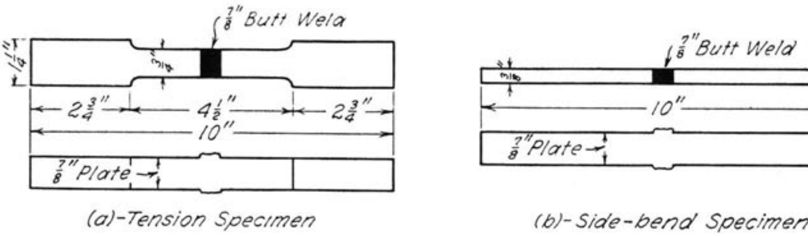


FIG. 43. SPECIMENS FOR TENSION AND SIDE-BEND TESTS OF WELDS

as the fatigue specimen, except that one number is supplemented with -1, as P11 and P11-1. The details of the static specimens, tension and side-bend, are shown in Fig. 43.

All static tension specimens broke outside of the weld and developed a strength equal to the static strength of the corresponding control specimen, given in Table 15, indicating that the flaws disclosed by fatigue fractures and by the metallurgical studies of Section 10 were not great enough to reduce the static strength of the weld below the original strength of the base plate. The appearance after failure is shown for a number of specimens in Fig. 44. It is of interest to note that, although no specimens failed in the weld, the tension did make the flaws more apparent.

The results of the side-bend tests are given in Table 23 and Figs. 45, 46, and 47. The specimens shown in the figures were polished and etched to disclose the flaws and the junction of the weld and base metal. The appearance of P15-1 of Fig. 46, and R3-1 of Fig. 47, is typical of specimens that contained no flaws. Likewise, XX5-1 of Fig. 45, P7 of Fig. 46, and R3 of Fig. 47 are typical of specimens that had flaws but that passed the side-bend test. Specimens XX9-1, R11, and P3-1 broke whereas XX15, P11-1, and R4 did not break but failed to pass. Specimens R11 and P3-1 show a distinct lack of penetration at the root of the weld.

The results of the side-bend test* are compared with the fatigue-strength ratings† of the specimens in Table 23. The information in this table indicates that there is no consistent relation between the results of the side-bend test and the fatigue-strength rating except that, in some instances, the specimens that pass the side-bend test

*For description of the Side-Bend Test of Butt Welds, see A.W.S. Specifications for Welded Highway and Railway Bridges (1941 Edition) pages 89, 96, and 98.

†The fatigue-strength rating of a specimen, as given in this table, is the ratio of the fatigue strength of that specimen to the average fatigue strength of the corresponding group of the basic series, given in Table 6.

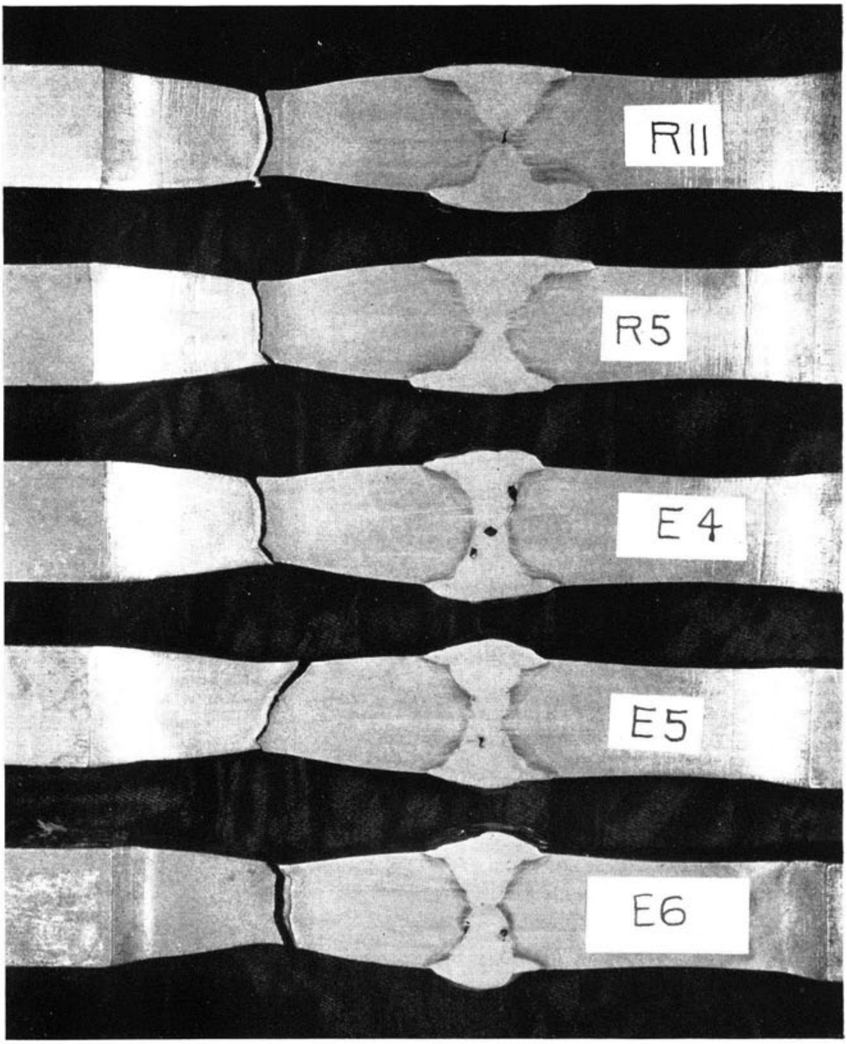


FIG. 44. STATIC TENSION SPECIMENS AFTER FAILURE

TABLE 23
RELATION BETWEEN RESULTS OF SIDE-BEND TEST AND FATIGUE-STRENGTH RATING
XX, P, and R Series

Specimen No.	Results of Side-Bend Test	Fatigue-Strength Rating	Location of Fatigue Fracture
XX5	Did not pass	1.08	In weld and at edge of weld.
XX5-1	Minor flaws		
XX9	Did not pass	1.04	At edge of weld.
XX9-1	Specimen broke at middle of weld.		
XX15	Did not pass	0.85	At edge of weld.
P1	Did not pass	1.00	At edge of weld.
P3	Minor flaws	1.01	At edge of weld.
P3-1	Specimen broke at middle of weld. Pronounced lack of penetration at root of weld.		
P7	Minor flaws	0.78	In weld and at edge of weld.
P9	Did not pass	0.87	At edge of weld.
P11	Did not pass	0.82	At edge of weld.
P11-1	Did not pass		
P15	Did not pass	0.80	At edge of weld.
P15-1	No flaws		
R1	Minor flaws	0.74	In weld.
R3	Minor flaws	1.06	At edge of weld.
R3-1	No flaws		
R4	Did not pass	1.00	Several inches from weld.
R4-1	Minor flaws		
R5	Minor flaws	0.74	In weld.
R6	No flaws	0.76	In weld.
R6-1	Very minor flaws		
R8	Very minor flaws	0.80	In weld.
R11	Specimen broke at middle of weld. Pronounced lack of penetration at root of weld.	0.88	In weld and at edge of weld.

have a higher fatigue-strength rating than those that do not. This, however, is not always true. Fatigue specimens XX5 and XX9 had fatigue-strength ratings of 1.08 and 1.04, whereas one of the two side-bend specimens for each of the two fatigue specimens failed to pass. In contrast with this, specimen R6 had a fatigue-strength rating of only 0.76 and the two adjacent side-bend specimens passed the side-bend test, one showing only very minor flaws, and the other showing no flaws that could be detected without magnification. In some other instances, the specimens that did not pass the side-bend test had a low fatigue strength. The lack of correlation between the results of the side-bend test and the fatigue test may be due to the fact that the side-bend test is a "sampling" test. The presence or absence of a flaw in one transverse strip across the weld ⅝ in. wide is not necessarily a dependable indication of the presence or absence of flaws along an adjacent 5-in. length of the weld.

12. *Discussion of Results.*—

XX Series

As shown in Table 20, the average fatigue strength for failure at 100 000 cycles was slightly greater for the XX than for the basic series. Moreover, the results were consistent, the minimum value for a group being slightly greater for the XX series than the average values for the corresponding group of the basic series. The same statements can be made relative to the fatigue strength for failure at 2 000 000 cycles insofar as it applies to the specimens tested on a cycle in which the stress varied from zero to tension; but the specimens of the XX series tested on a cycle in which the stress varied from tension to an equal compression, although consistent with each other, had a lower fatigue strength for failure at 2 000 000 cycles than the basic series, the ratio of average values and the ratio minimum-to-average values for the group being 0.89 and 0.85, respectively.

All static tension specimens failed outside of the weld. The specimen weakest in fatigue, XX15, failed to pass the side-bend test. Specimens XX5 and XX9, which had more than average fatigue strength, also failed to pass the side-bend test. Although the XX specimens, tested for failure at 2 000 000 repetitions of a cycle in which the stress varied from tension to an equal compression, had a lower fatigue strength than the corresponding group of the basic series, the XX series as a whole was the strongest and most consistent of any of the series of commercial welds tested. The radiographs showed that all specimens had considerable porosity, but it consisted of small voids quite uniformly distributed through the weld metal, and seemed to be less injurious than the external stress raiser due to the change in section at the edge of the reinforcement.

The fabricator who made the XX specimens had previously made the X specimens. Moreover, before the XX specimens were welded, the welding superintendent had examined the fatigue fractures of the X specimens and realized the character of the flaws that caused the fatigue strength of some of them to be low. The inspector from the inspection bureau, under whose supervision the welds of the XX series were made, had also been informed of the character of the flaws in the X specimens. It is possible that a knowledge of the nature of the flaws in the X series may have reduced slightly the magnitude of similar flaws in the XX series.

Series P

The S-N diagrams of Fig. 39(b) show that the tests of series P were fairly consistent, but the fatigue strength was low for a few specimens.

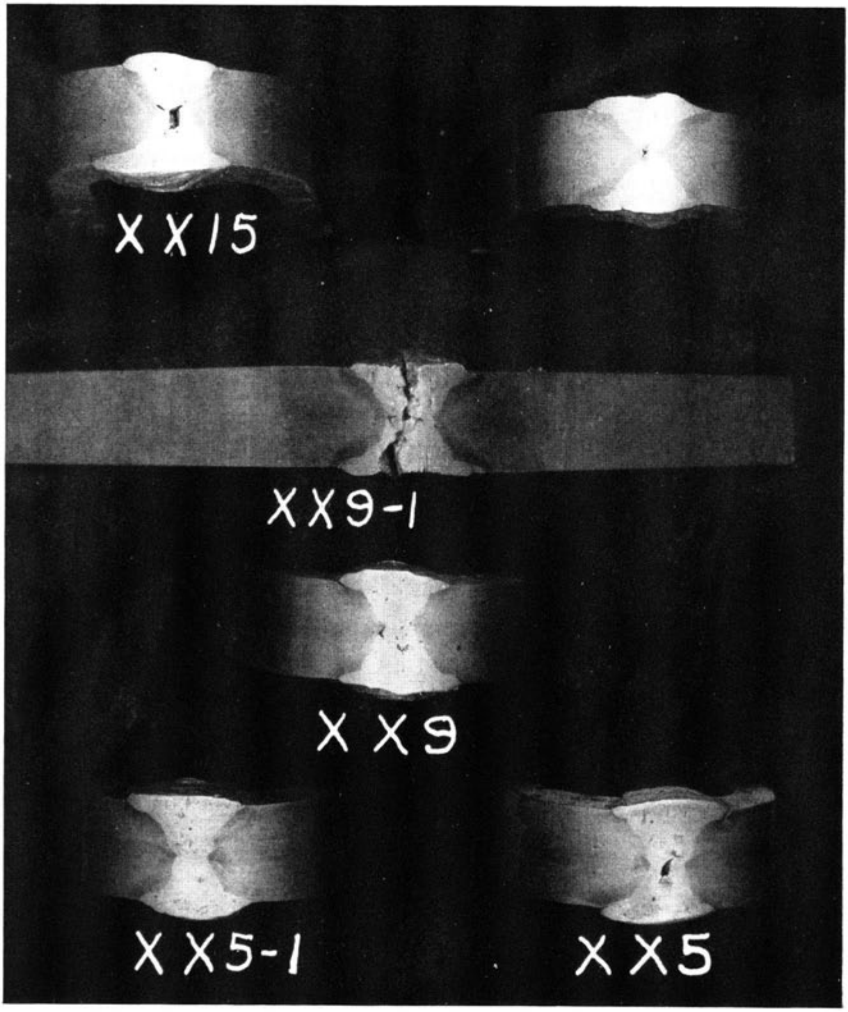


FIG. 45. SIDE-BEND SPECIMENS AFTER TESTS. XX SERIES

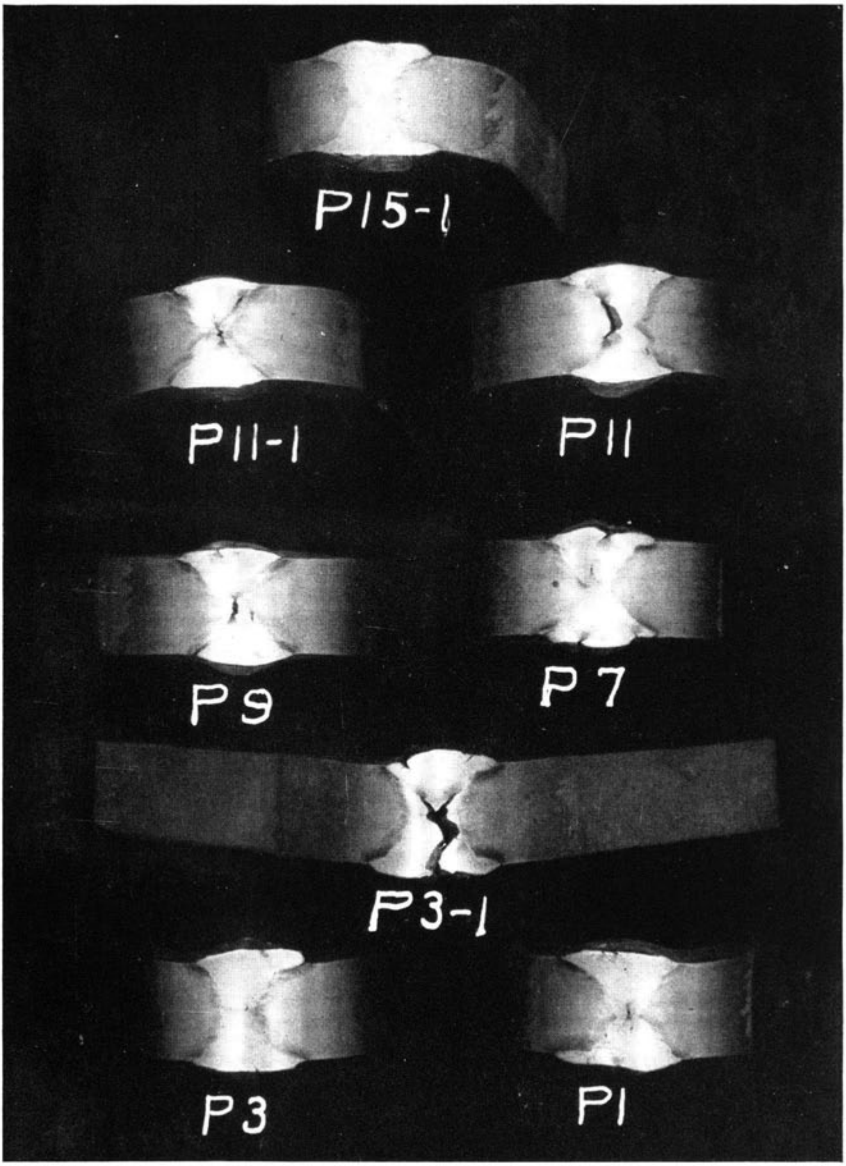


FIG. 46. SIDE-BEND SPECIMENS AFTER TESTS. P SERIES

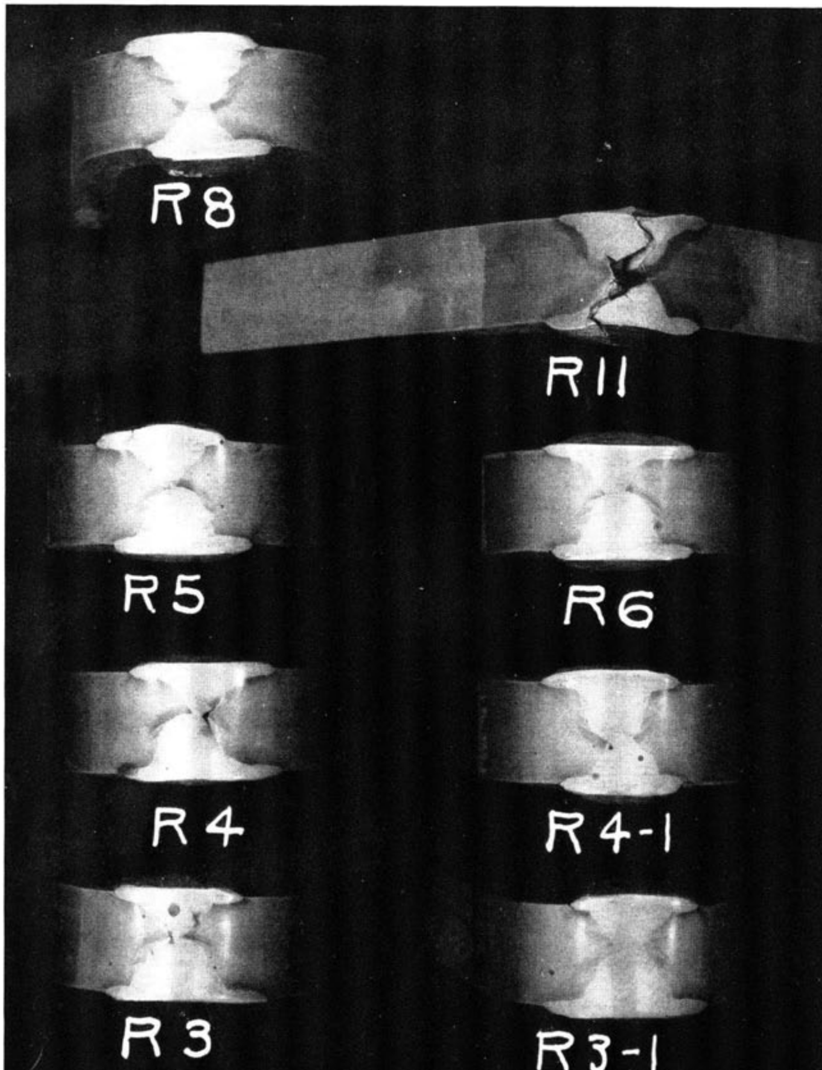


FIG. 47. SIDE-BEND SPECIMENS AFTER TESTS. R SERIES

The ratio of averages had values of 1.03 and 0.95 for failure at 100 000 and 2 000 000 cycles, respectively, for a cycle in which the stress varied from zero to tension. The corresponding values were 0.84 and 0.82 for a complete reversal of stress. The ratio minimum-to-average had values of 1.00 and 0.90 for failure at 100 000 and 2 000 000 cycles, respectively, for a cycle in which the stress varied from zero to tension. The corresponding values were 0.80 and 0.77 for a complete reversal of stress. Two specimens, P9 and P10, broke in the weld. P9 had a low, and P10 a high fatigue strength. Three specimens, P4, P7, and P11, broke both in the weld and at the edge of the weld; P7 and P11 had low fatigue strengths. All of the other specimens broke at the edge of the weld.

All static tension specimens broke outside of the weld; six of the nine side-bend specimens failed to pass the test, but, with the exception of P7, the corresponding fatigue specimens broke at the edge of the reinforcement.

The fabricator who welded the P specimens had previously welded the Z specimens. Moreover, the fabricator and the inspector for the P specimens had been informed of the character of the flaws in the Z specimens prior to the welding of the P specimens. Nevertheless, the P specimens were only slightly, if any, better than the Z specimens.

Series R

The *S-N* diagrams of Fig. 39(c) show that the tests of series R were very inconsistent. The ratio of averages had values of 1.05 and 0.99 for failure at 100 000 and 2 000 000 cycles, respectively, for a cycle in which the stress varied from zero to tension. The corresponding values were 0.97 and 0.82 for a complete reversal of stress. The ratio minimum-to-average had values of 0.98 and 0.76 for failure at 100 000 and 2 000 000 cycles, respectively, for a cycle in which the stress varied from zero to tension. The corresponding values were 0.88 and 0.74 for a complete reversal of stress. As shown in Table 22, many of the specimens broke in the weld; only R4 broke entirely outside of the weld. It had a considerably higher fatigue strength than others of its group that failed in the weld. The fractures of all specimens that failed in the weld showed a lack of penetration at the root of the weld.

All static tension specimens broke outside of the weld; two of the side-bend specimens failed to pass the test, but the fatigue strength was not particularly low for either of the corresponding fatigue specimens.

13. *Summary*.—The results of the six series of commercial butt welds in ⅞-in. carbon-steel plates welded in the flat position with a

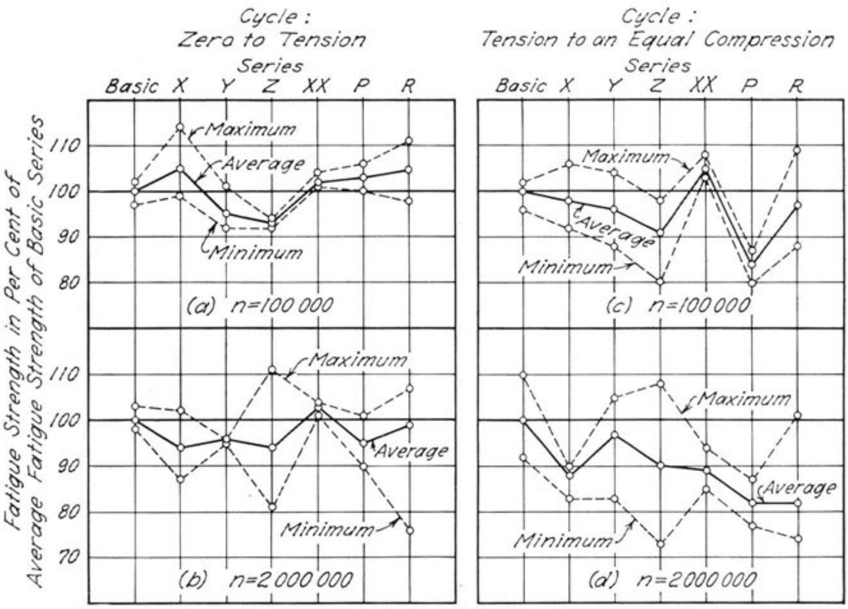


FIG. 48. COMPARISON OF FATIGUE STRENGTHS OF VARIOUS SERIES OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES

manually-operated metallic arc, summarized in Tables 7 and 20, are shown graphically by the diagrams of Fig. 48. Figures 48a and 48b are for specimens tested on a cycle in which the stress varied from zero to tension, 48a being for failure at 100 000 cycles and 48b for failure at 2 000 000 cycles. Likewise, Figs. 48c and 48d are for specimens tested on a cycle in which the stress varied from tension to an equal compression, 48c being for failure at 100 000 cycles and 48d for failure at 2 000 000 cycles. The series designations, basic, X, Y, etc., are given above the diagrams in each instance. Each group consists of three diagrams; the upper one represents the maximum value, the lower one the minimum value, and the middle one the average value for a group. All values are expressed in percentage of the average value of the corresponding group of the basic series. It is to be noted that the results were more consistent for some commercial series than for the basic series.

The average and minimum values of the fatigue strength, for various ratios of minimum-to-maximum stress in the stress cycle and for failure at 100 000 and 2 000 000 repetitions, are given in Table 24. Two sets of values are given, the upper one includes only the basic

TABLE 24

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN $\frac{7}{8}$-IN. CARBON-STEEL PLATES

Basic, X, Y, Z, XX, P, and R Series

All specimens welded in the flat position with a manually-operated metallic arc. All specimens tested in the as-welded condition.

All values of fatigue strength given in lb. per sq. in. of gross section of plate.

	Cycle			
	Zero to Tension		Tension to an Equal Compression	
	$n = 100\ 000$	$n = 2\ 000\ 000$	$n = 100\ 000$	$n = 2\ 000\ 000$
Basic Series				
Number of tests	4	3	3	4
Average fatigue strength for all tests	33 100	22 500	22 300	14 400
Minimum fatigue strength for any one test	32 000	22 100	21 400	13 300
X, Y, Z, XX, P, and R Commercial Series				
Number of tests	19	21	19	21
Average fatigue strength for all tests	33 200	21 700	21 300	12 700
Minimum fatigue strength for any one test	30 400	17 100	17 900	10 500

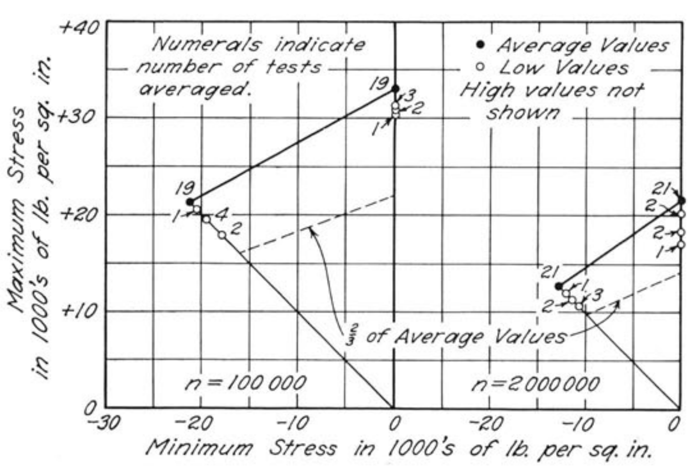


FIG. 49. FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN $\frac{7}{8}$-IN. CARBON-STEEL PLATES. SUMMARY

series; the lower one includes all of the commercial series. It is of interest to note that the two sets of averages do not differ greatly, but that the minima are much less for the commercial than for the basic series for some categories.

Average values for the commercial series are represented by the full-line diagrams of Fig. 49. The numerals adjacent to the solid circles indicate the number of tests averaged, and the small open circles represent individual tests that gave less than average values of the fatigue strength. A numeral adjacent to an open circle indicates the number of tests that gave that particular fatigue strength.

The broken lines represent two-thirds of the average values of the fatigue strength. It is of interest to note that all values fall well above the broken lines.

The XX, P, and R series, which were welded under the supervision of an inspector employed by Committee F, were neither significantly better nor significantly poorer than the X, Y, and Z series which were not supervised by an outside inspector.

IV. Specimens Welded in Various Positions and With Various Electrodes
Series A, B, C, D, E, F, G, S, T, and U; Group 3

14. *Description of Specimens.*—The specimens for the X, Y, Z, XX, P, and R series were all welded in the flat position; the specimens used in the tests described in this chapter were butt welds in ⅞-in. carbon-steel plates welded in various positions and with various electrodes, as indicated in Table 25. The plates were rolled from the same heat as the plates used for the XX, P and R series, described in Section 8. The specimens were made by commercial fabricators and the welding was done by qualified operators* working under the supervision of an inspector from an inspection bureau employed by the Fatigue Committee. In each instance, the welding operator had had experience with the electrode that he used in welding the specimens. The details of the welding procedure for the various series are shown in Figs. 50 and 51. Some specimens of each series were tested on a cycle in which the stress varied from zero to tension, others on a cycle in which the stress varied from tension to an equal compression. The dimensions of the specimens were the same as for the basic series shown in Fig. 1. All specimens were tested in the as-welded condition.

*See note, Table 25.

TABLE 25

POSITION OF WELDING AND CLASSIFICATION OF ELECTRODE FOR COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES

Welding specified to be done in accordance with the American Welding Society's 1941 Specifications for Welded Highway and Railway Bridges by a qualified welder working under an inspector furnished by Committee F.

Series	Electrode Classification No.	Type of Groove	Welding Position
A B C	E6010 E6012 E6013	Symmetrical double V	Welded in the flat position from one side and in the overhead position from the other side.
D E F	E6010 E6012 E6013	Symmetrical double V	Welded in vertical position from both sides.
G	E6030 for flat position E6010 for overhead position	Single U	U side welded in flat position and the other side in the overhead position after proper back-chipping to sound metal.
S T U	E6010 E6020 E6030	Symmetrical double V	Welded in the flat position from one side, then turned over and welded in the flat position from the other side.

15. *Results of Tests.*—The results of the tests are given in Tables 26 to 29, inclusive; the type of groove and the position for welding are given in the title and the A.W.S.-A.S.T.M. electrode classification is given in the body of the table in each instance. The number of cycles for failure and the fatigue strength corresponding to failure at 100 000 or 2 000 000 cycles are given. The fatigue strength was computed from the number of cycles for failure by use of the equation $F = S\ (N/n)^K$, in which F is the fatigue strength corresponding to failure at n cycles, S and N are the maximum stress in the stress cycle and number of cycles for failure, respectively, and K is an experimental constant. The individual tests of the same series were quite inconsistent and there were not enough specimens with the same groove, electrode, and position of welding to establish a value of K from these tests alone. The constant K was therefore assigned a value of 0.13, the value previously used in Bulletin 327 for butt welds with the reinforcement on. Where the ratio (N/n) had values between 2.5 and 0.40, a considerable error in the value of K would make only a relatively small error in the computed fatigue strength.* In the few instances in which the value of N/n fell considerably outside of this range (2.5 to 0.40), the computed values may be considerably in error. However, no more acceptable method is available for getting probable values from a few highly erratic tests.

*Report No. 2, Committee F.

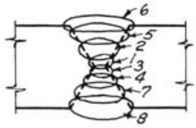
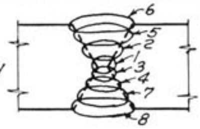
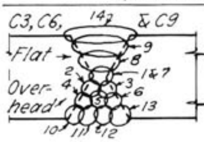
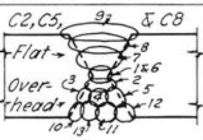
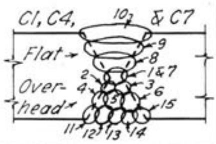
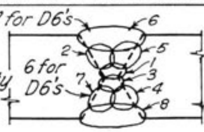
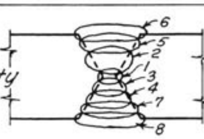
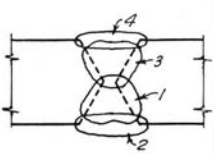
Weld	Pass No.	Position	Elect. Size	Voltage	Current, Amperes
Specimen Number: A4-1, A4-2, A4-3, A5-1, A5-2, A5-3, A6-1, A6-2, A6-3					
A.W.S. E-6010 D.C. Reversed Polarity Machined Groove 	1,2 3,4,7,8 5,6	Flat Overhead Flat	5/32" 5/32" 1/4"	25-30 25-30 30-35	110-160 110-160 225-375
Specimen Number: B4-1, B4-2, B4-3, B5-1, B5-2, B5-3, B6-1, B6-2, B6-3					
A.W.S. E-6012 D.C. Straight Polarity Machined Groove 	1,2 3,4,7,8 5,6	Flat Overhead Flat	5/32" 5/32" 1/4"	22-25 22-25 24-28	90-200 110-160 275-500
Specimen Number: C1, C2, C3, C4, C5, C6, C7, C8, C9					
   A.W.S. E-6013 A.C. 25 Cycles Gas Cut	1 Others Others	Flat Overhead Flat	5/32" 5/32" 3/16"	23 22 25	200 180 240
Specimen Number: D4-1, D4-2, D4-3, D5-1, D5-2, D5-3, D6-1, D6-2, D6-3					
A.W.S. E-6010 D.C. Reversed Polarity Machined Groove 	1,2 3 to 8	Vertical Vertical	5/32" 5/32"	25 27-32	110-160 110-150
	D5-1, D5-2, D5-3, D6-1, D6-2, D6-3 same as above except all passes have welding current of 110-160 amperes.				
Specimen Number: E4-1, E4-2, E4-3, E5-1, E5-2, E5-3, E6-1, E6-2, E6-3					
A.W.S. E-6012 D.C. Straight Polarity Machined Groove 	1 to 8	Vertical	5/32"	21-28	110-170
Specimen Number: F1, F2, F3, F4, F5, F6, F7, F8, F9					
A.W.S. E-6013 A.C. 25 Cycles Gas Cut 	For F1, F2, F4, F5, F7 & F8				
	1,2 3 4	Vertical Vertical Vertical	5/32" 5/32" 3/16"	23 24 24	175 190 200
	F3, F-6, & F9 as above, except:				
	4	Vertical	5/32"	23	170

Fig. 50. Welding Procedure. Commercial Butt Welds in 7/8-in. Carbon-Steel Plates. Series A, B, C, D, E, and F

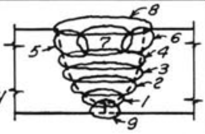
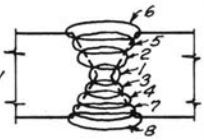
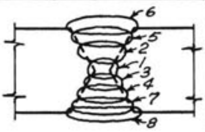
Welds		Pass No.	Position	Elect. Size	Voltage	Current, Amperes
Specimen Number: G4-1, G4-2, G4-3; G5-1, G5-2, G5-3; G6-1, G6-2, G6-3						
Flat—A.W.S. E-6030 Overhead— A.W.S. E-6010 D.C. Reversed Polarity Machined Groove		1 2 to 8 9	Flat Flat Overhead	$\frac{3}{16}''$ $\frac{1}{4}''$ $\frac{3}{16}''$	24-30 29-37 25-30	175-250 275-375 110-160
Specimen Number: S4-1, S4-2, S4-3; S5-1, S5-2, S5-3; S6-1, S6-2, S6-3						
A.W.S. E-6010 D.C. Reversed Polarity Machined Groove		1,2 3 to 8	Flat Flat	$\frac{3}{16}''$ $\frac{1}{4}''$	28-32 35-40	175-225 250-300
Specimen Number: T4-1, T4-2, T4-3; T5-1, T5-2, T5-3; T6-1, T6-2, T6-3						
A.W.S. E-6020 D.C. Straight Polarity Machined Groove		T4-1, T4-2, & T4-3				
		1,2 3 to 8	Flat Flat	$\frac{3}{16}''$ $\frac{1}{4}''$	28-32 35-40	175-225 250-300
		T5-1, T5-2, & T5-3				
		1,2 3 to 8	Flat Flat	$\frac{3}{16}''$ $\frac{1}{4}''$	30-35 30-35	150-200 250-300
		T6-1, T6-2, & T6-3				
		1,2 3 to 8	Flat Flat	$\frac{3}{16}''$ $\frac{1}{4}''$	Min. 30 30-35	140-350 175-500
Specimen Number: U4-1, U4-2, U4-3; U5-1, U5-2, U5-3; U6-1, U6-2, U6-3						
A.W.S. E-6030 D.C. Straight Polarity Machined Groove		1,2 3 to 8	Flat Flat	$\frac{3}{16}''$ $\frac{1}{4}''$	Min. 30 30-35	150-250 250-400

FIG. 51. WELDING PROCEDURE. COMMERCIAL BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES. SERIES G, S, T, AND U

TABLE 26

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WELDED IN FLAT POSITION

Symmetrical Double V Groove

Specimen No.	Electrode	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Cracks*
				$n =$ 100 000	$n =$ 2 000 000	
S5-1	E6010	0 to 25.0	212.0	27.6		1, 2
S5-2		0 to 25.0	443.1	30.3		1, 2
S5-3		0 to 25.0	1089.2	34.1		1, 2
Av.			581.5	30.7		
S6-1		+20.0 to −20.0	225.9	22.2		2
S6-2		+20.0 to −20.0	238.4	22.4		2
S6-3		+20.0 to −20.0	85.3	19.6		2, 3
Av.			183.2	21.4		
S4-1		+16.0 to −16.0	613.0		13.7	2, 3
S4-2		+16.0 to −16.0	733.9		14.0	2
S4-3		+16.0 to −16.0	805.8		14.2	2, 3
Av.			717.6		14.0	
T6-1	E6020	0 to 25.0†	680.5	32.1		1, 2, 3
T6-2		0 to 25.0	394.8	29.9		1
T6-3		0 to 25.0	1055.6	34.0		2, 3
Av.			710.3	32.0		
T5-1		+20.0 to −20.0	152.7	21.1		3
T5-2		+20.0 to −20.0	188.1	21.7		2
T5-3		+20.0 to −20.0	305.1	23.1		1
Av.			215.3	22.0		
T4-1		+16.0 to −16.0	1059.4		14.7	2
T4-2		+16.0 to −16.0	440.2		13.1	2
T4-3		+16.0 to −16.0	360.7		12.8	2, 3
Av.			620.1		13.5	
U4-1	E6030	0 to 25.0	161.8	26.6		1, 2
U4-2		0 to 25.0	178.2	27.0		2
U4-3		0 to 25.0	244.7	28.1		2, 3
Av.			194.9	27.2		
U6-1		0 to 20.0	4354.4		20.0+	2
U6-2		0 to 20.0	7908.1†		20.0+	(†)
U6-3		0 to 20.0	1548.3		19.3	1
Av.			4603.6		19.8+	
U5-1		+16.0 to −16.0	955.2		14.5	2, 3
U5-2		+16.0 to −16.0	470.0		13.3	4
U5-3		+16.0 to −16.0	452.0		13.2	2
Av.			625.7		13.7	

*See Fig. 4.
†Did not fail.

The results of the tests, given in detail in Tables 26 to 29, inclusive, are summarized in Table 30. The first part of the table contains values of the fatigue strength corresponding to failure at 100 000 cycles and the second part contains values corresponding to failure at 2 000 000 cycles. The upper half of each part contains the average values for a group of identical tests and the lower half contains the minimum value for an individual test of the corresponding group. There are two lines for each category; the upper lines contain values of the fatigue strength in thousands of pounds per square inch, and

Table 27

Fatigue Strength of Commercial Butt Welds in 7/8-in. Carbon-Steel Plates Welded in Vertical Position

Symmetrical Double V Groove

Specimen No.	Electrode	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Cracks*
				$n =$ 100 000	$n =$ 2 000 000	
D5-1	E6010	0 to 25.0	353.0	29.5		3
D5-2		0 to 25.0	198.1	27.3		2, 3
D5-3		0 to 25.0	164.7	26.7		2
Av.			238.6	27.8		
D6-1		0 to 20.0	1669.4		19.5	1
D6-2		0 to 20.0	1365.9		19.0	2, 3
D6-3		0 to 20.0	1691.2		19.5	2
Av.			1575.5		19.3	
D4-1		+16.0 to −16.0	80.7	15.6	10.5	1
D4-2		+16.0 to −16.0	246.0	18.1	12.2	2, 3
D4-3		+16.0 to −16.0	155.8	17.0	11.5	1, 2
Av.			160.8	16.9	11.4	
E4-1	E6012	0 to 30.0	83.4	29.3		2
E4-2		0 to 30.0	136.7	31.2		2
E4-3		0 to 30.0	83.0	29.3		1
Av.			97.7	29.9		
E5-1		0 to 25.0	334.8	29.3		1, 2
E5-2		0 to 25.0	364.0	29.5		1, 2
E5-3		0 to 25.0	475.5	30.6		2
Av.			391.4	29.8		
E6-1		0 to 20.0	724.8		17.5	2
E6-2		0 to 20.0	910.6		18.1	2, 3
E6-3		0 to 20.0	1265.7		18.8	3
Av.			967.0		18.1	
F1	E6013	0 to 25.0	525.6	30.9	21.0	2, 3
F2		0 to 25.0	550.1	31.2	21.1	2
F3		0 to 25.0	802.2	32.8	22.2	1, 2
Av.			625.9	31.6	21.3	
F6		+20.0 to −20.0	161.5	21.3		1
F7		+20.0 to −20.0	197.3	21.8		1
F9		+20.0 to −20.0	160.1	21.3		1
Av.			173.0	21.5		
F4		+16.0 to −16.0	603.5		13.7	2
F5		+16.0 to −16.0	616.3		13.7	1
F8		+16.0 to −16.0	504.4		13.4	1, 2
Av.			574.7		13.6	

*See Fig. 4.

the lower lines contain the ratios of the average or the minimum values, as the case may be, to the average values for the corresponding groups of the basic series. The latter values, given in column 2 of the table, are the same as those used in the study of the X, Y, Z, XX, P, and R series of Tables 7 and 20.

16. *Metallurgical Studies.*—The metallurgical studies of specimens welded in various positions and with various electrodes included hardness surveys and an examination of macrostructures and microstructures of the weld metal and the heat-affected zone.

TABLE 28

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WELDED IN FLAT POSITION FROM ONE SIDE AND OVERHEAD POSITION FROM OTHER SIDE

Symmetrical Double V Groove

Specimen No.	Electrode	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Cracks*
				$n =$ 100 000	$n =$ 2 000 000	
A4-1	E6010	0 to 30.0	521.2	37.2		2
A4-2		0 to 30.0	254.6	33.9		2, 3
A4-3		0 to 30.0	447.8	36.5		1, 2
Av.			407.9	35.9		
A6-1		0 to 25.0	399.3	29.9		2
A6-2		0 to 25.0	278.4	28.6		1, 2
A6-3		0 to 25.0	558.4	31.3		1, 2
Av.			412.0	29.9		
A5-1		0 to 20.0	499.7		16.7	2
A5-2		0 to 20.0	451.3		16.5	2
A5-3		0 to 20.0	852.0		17.9	2
Av.			601.0		17.0	
B4-1	E6012	0 to 30.0	275.7	34.2		2
B4-2		0 to 30.0	438.3	36.4		2
B4-3		0 to 30.0	401.1	35.9		1
Av.			371.7	35.5		
B5-1		0 to 25.0	441.0	30.3		1, 2
B5-2		0 to 25.0	372.1	29.6		2
B5-3		0 to 25.0	362.3	29.5		1, 2
Av.			391.8	29.8		
B6-1		0 to 20.0	2739.1		20.0+	2
B6-2		0 to 20.0	4543.6		20.0+	2, 3
B6-3		0 to 20.0	1611.2		19.4	2, 3
Av.			2964.6		20.0+	
C4	E6013	0 to 30.0	266.6	34.0		3
C5		0 to 30.0	468.5	36.6		2, 3
C6		0 to 30.0	331.0	35.0		2, 3
Av.			355.4	35.2		
C1		0 to 25.0	781.0	32.7	22.1	1, 2
C2		0 to 25.0	1051.5	33.9	23.0	2
C3		0 to 25.0	576.6	31.4	21.3	2
Av.			803.0	32.7	22.1	
C7		0 to 20.0	954.8		18.2	2
C8		0 to 20.0	1882.4		19.8	2
C9		0 to 20.0	1530.7		19.3	2, 3
Av.			1456.0		19.3	

*See Fig. 4.

Hardness Tests

Hardness surveys similar to those described in Section 5 were made on specimens that had been subjected to a fatigue test, either one or two specimens from each of the series A to G, inclusive. Similar hardness tests were made on an untested portion of the weld cut from the parent welded plate from which the specimens for series S, T, and U were cut.

The hardness values obtained from these tests are given in Table 31. The minimum and maximum values reported are individual readings,

TABLE 29

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WELDED IN FLAT POSITION FROM U SIDE AND OVERHEAD POSITION FROM OTHER SIDE

Single U Groove

Specimen No.	Electrode	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength in 1000's of lb. per sq. in.		Location of Fatigue Cracks*
				$n =$ 100 000	$n =$ 2 000 000	
G5 1	E6030	0 to 25.0	277.2	28.5	19.3	2, 3
G5 2	For flat	0 to 25.0	120.2	25.6	17.3	2, 3
G5 3	position	0 to 25.0	659.6	32.0	21.6	1, 2, 3
Av.			352.3	28.7	19.4	
G6 1	E6010	+20.0 to −20.0	132.2	20.7		2, 3
G6 2	For	+20.0 to −20.0	119.2	20.5		2, 3
G6 3	overhead	+20.0 to −20.0	68.0	19.0		2, 3
Av.	position		106.5	20.1		
G4 1		+16.0 to −16.0	727.1		14.0	3
G4 2		+16.0 to −16.0	1006.0		14.6	2
G4 3		+16.0 to −16.0	345.3		12.7	2
Av.			692.8		13.8	

*See Fig. 4.

the average values represent the average ordinates of the hardness diagrams based on individual readings. The heat-affected zones of the specimens of the C and G series were hardened to a considerable extent, the maximum hardness values being 301 and 280 Vickers for series C and G, respectively. The maximum hardness in the same region was slightly greater than 200 Vickers for the specimens of the A and E series and was less than 200 Vickers for the other series of this group.

The high hardness number of 301 Vickers in specimen C9 resulted from the stringer beads that were placed in the overhead position. The hardness on the other side of this specimen, where the weld was made in the flat position with a 3/16-in. electrode and 240 amperes, had a maximum value of less than 200 Vickers. The maximum hardness of 280 Vickers in Specimen G43 was where the series-3 line of indents crossed the heat-affected zone resulting from the final root weld placed with a 3/16-in. electrode and a low current. The maximum hardness on the other side of this specimen was less than 180 Vickers.

The average hardness of the unaffected base metal, the total range for all specimens of the 10 series in the group, varied from 130 to 155 Vickers.

The highest individual hardness readings of the weld metal were on the specimens of the B and E series welded with the E6012 electrodes. The weld metal deposited with an E6013 electrode had a

TABLE 30

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WELDED IN VARIOUS POSITIONS AND WITH VARIOUS ELECTRODES; SUMMARY OF RESULTS

Each value is the average of three tests except as noted

Stress Cycle	Welded in Flat Position				Welded in Vertical Position			Welded in Flat Position From One Side and in Overhead Position From Other Side			
	Single U Groove	Symmetrical Double V Groove			Symmetrical Double V Groove			Symmetrical Double V Groove			Single U Groove
	Basic Series	S Series E6010	T Series E6020	U Series E6030	D Series E6010	E Series E6012	F Series E6013	A Series E6010	B Series E6012	C Series E6013	G Series, E6030 for Flat Position E6010 for Overhead Position
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Average Values n = 100 000											
Zero to tension	33.1 1.00	30.7 0.93	32.0 0.97	27.2 0.82	27.8 0.84	29.9 0.90	31.6 0.95	32.9* 0.99	32.7† 0.99	34.0‡ 1.03	28.7 0.87
Tension to equal compression	22.3 1.00	21.4 0.96	22.0 0.99	.....	16.9 0.76	.....	21.5 0.96	.....	.....	.....	20.1 0.90
Minimum Values n = 100 000											
Zero to tension	32.0 0.97	27.6 0.83	29.9 0.90	26.6 0.80	26.7 0.81	29.3 0.89	30.9 0.93	28.6 0.86	29.5 0.89	31.4 0.95	25.6 0.77
Tension to equal compression	21.4 0.96	19.6 0.88	21.1 0.95	.....	15.6 0.70	.....	21.3 0.96	.....	.....	.....	19.0 0.85

TABLE 30 (CONCLUDED)

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WELDED IN VARIOUS POSITIONS AND WITH VARIOUS ELECTRODES; SUMMARY OF RESULTS

Each value is the average of three tests except as noted

Stress Cycle	Welded in Flat Position				Welded in Vertical Position			Welded in Flat Position From One Side and in Overhead Position From Other Side			
	Single U Groove	Symmetrical Double V Groove			Symmetrical Double V Groove			Symmetrical Double V Groove			Single U Groove
	Basic Series	S Series E6010	T Series E6020	U Series E6030	D Series E6010	E Series E6012	F Series E6013	A Series E6010	B Series E6012	C Series E6013	G Series, E6030 for Flat Position E6010 for Overhead Position
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Average Values $n = 2\ 000\ 000$											
Zero to tension	22.5 1.00	.....	.....	19.8 0.88	19.3 0.86	18.1 0.80	21.3 0.95	17.0 0.76	20.0 0.89	20.7¶ 0.92	19.4 0.86
Tension to equal compression	14.4 1.00	14.0 0.97	13.5 0.94	13.7 0.95	11.4 0.79	.....	13.6 0.94	.....	.....	.....	13.8 0.96
Minimum Values $n = 2\ 000\ 000$											
Zero to tension	22.1 0.98	.....	.....	19.3 0.86	19.0 0.84	17.5 0.78	21.0 0.93	16.5 0.73	19.4 0.86	18.2 0.81	17.3 0.77
Tension to equal compression	13.3 0.92	13.7 0.95	12.8 0.89	13.2 0.92	10.5 0.73	....	13.4 0.93	....	....	....	12.7 0.88

*Average of A4-1, A4-2, A4-3, A6-1, A6-2, and A6-3, Table 28.
†Average of B4-1, B4-2, B4-3, B5-1, B5-2, and B5-3, Table 28.
‡Average of C1, C2, C3, C4, C5, and C6, Table 28.
¶Average of C1, C2, C3, C7, C8, and C9, Table 28.

TABLE 31
VICKERS HARDNESS NUMBERS FOR SPECIMENS WELDED IN VARIOUS POSITIONS AND WITH VARIOUS ELECTRODES

Specimen No.	Series	Unaffected Base Metal			Heat-Affected Base Metal	Weld Metal			Electrode
		Maximum	Minimum	Average	Maximum	Maximum	Minimum	Average	
A41	1	174	123	140	222	179	147	153	E6010
	2				162	163	153	155	
	3				208	158	148	155	
								Av. 154	
B43	1	168	129	142	198	196	161	177	E6012
	2	162	127	140	185	216	197	202	
	3	147	130	142	187	172	158	166	
								Av. 182	
B52	1	137	124	132	191	160	153	158	E6012
	2	149	117	132	177	177	168	174	
	3	135	122	130	188	167	155	163	
								Av. 165	
C9	1	157	142	150	301	184	169	185	E6013
	2	158	122	138	184	188	179	182	
	3	168	144	155	196	189	173	180	
								Av. 182	
D51	1	140	124	132	177	146	140	143	E6010
	2	144	110	130	168	158	152	155	
	3	141	132	137	197	153	137	144	
								Av. 147	
E41	1	143	122	128	184	158	149	154	E6012
	2	160	122	135	208	193	180	184	
	3	147	124	135	192	184	145	165	
								Av. 168	
E62	1	143	122	130	204	184	160	168	E6012
	2	160	118	135	179	180	150	170	
	3	163	125	140	211	161	158	159	
								Av. 166	
F4	1	152	124	140	192	183	174	180	E6013
	2	158	134	148	191	175	151	160	
	3	145	117	130	184	168	144	162	
								Av. 167	
G43	1	147	133	141	175	154	130	144	E6030
	2	160	134	146	212	180	161	170	E6010
	3	157	142	152	280	183	170	177	
								Av. 164	
S	1	140	127	135	192	166	145	155	E6010
	2	159	134	148	175	155	142	150	
	3	142	127	135	186	157	148	154	
								Av. 153	
T	1	136	123	130	168	151	142	146	E6020
	2	146	127	140	158	140	133	138	
	3	140	130	134	180	160	143	155	
								Av. 146	
U	1	145	134	140	189	153	144	150	E6030
	2	162	138	150	181	146	145	145	
	3	148	126	145	195	143	140	142	
								Av. 146	

greater average hardness than the weld metal deposited with an E6010 electrode. This was true for the C and A specimens both of which had symmetrical double V grooves welded in the flat position from one side and in the overhead position from the other side; it was also true for the F and D specimens, both of which had symmetrical double V grooves welded in the vertical position from both sides. The average hardness of the weld metal of specimens S, T, and U, all of which had symmetrical double V grooves welded in the flat position from both sides, decreased with the electrodes in the order E6010, E6020, and E6030. However, the range in the average hardnesses for a specimen was quite small, from 182 Vickers for B43 and C9 to 146 Vickers for T and U. The maximum hardness in the weld metal was lower than the maximum hardness in the heat-affected zone for all specimens surveyed except B43.

Microstructures

The miscrostructure of the base metal and the weld metal was examined for all specimens used in the hardness surveys. The unaffected base metal appeared to have the same structure for all specimens. The size of the prior austenite grains of the heat-affected zone had a narrow range from the minimum in specimen F9 to the maximum in specimen B63, both of which are shown in Fig. 52. Except for minor differences in grain size, the microstructure was of similar character except for specimens C9 and G43. An acicular structure was found in the metal adjacent to the fusion line for these two specimens. However, the acicular structure, while of considerably higher hardness than the usual pearlitic structure, appeared to be of the character of bainite, which has considerable toughness, rather than of the character of martensite, which usually has low ductility.

A survey of the weld metal deposited with different electrodes and in various positions showed no significant difference in the number or type of microscopic inclusions. However there were differences in the inclusions of macroscopic size, and there were differences between the size and length of the columnar grains and in the recrystallized grains of the weld metal, but these differences could have been due largely to the different welding procedures used.

Welding Defects

Undercutting, porosity, and slag inclusions of varied macroscopic size were usually associated with that part of the weld which had been placed in the overhead position for the specimens of the A, B, and C

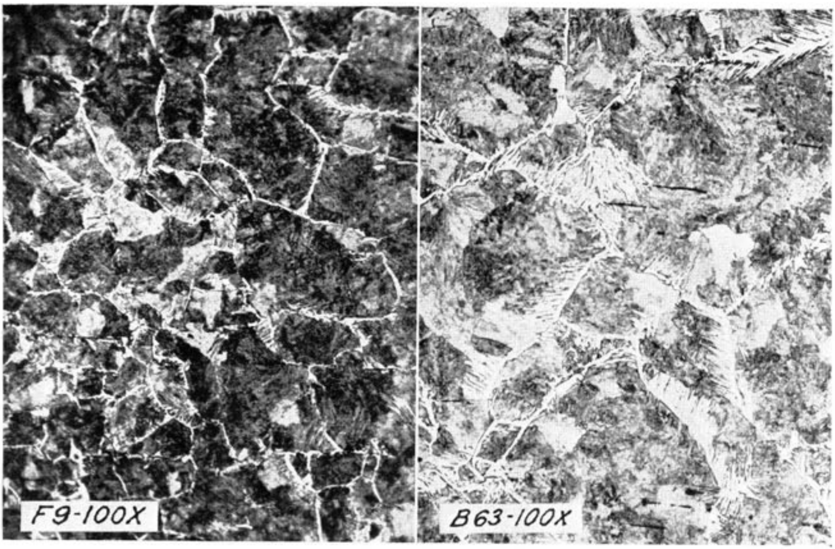


FIG. 52. MICROSTRUCTURE OF HEAT-AFFECTED ZONE. SPECIMENS F9 AND B63

series. Evidences of undercutting, porosity, and the presence of slag inclusions were also found in the specimens of the D, E, and F series, which were welded in the vertical position. The E specimens were particularly bad with respect to the number and extent of unfused areas and regions containing slag, especially in the two root beads on either side of the V. The appearance of the weld area of various specimens after etching with 50-50 HCl-water at 150 deg. F., is shown in Figs. 53 and 54. Figure 53 shows specimens A42, B62, and C7 with the side of the weld placed in the flat position at the top and the portion welded in the overhead position at the bottom. The latter portion of the weld is easily recognized by the uneven, serrated contour produced on the surface of the weld. The slag inclusion and lack of penetration at the root of the weld of specimen E41 is shown in Fig. 54.

The welds in the specimens of the S, T, and U series were judged to be of highest quality with respect to general lack of defects, low amount of porosity, and general excellence of the weld microstructure. The summary given in Table 30 shows that, in general, they had a high fatigue strength, although the U specimens tested for failure at 100 000 cycles were somewhat weaker than the others.

The classification of failures shown in Table 32 indicates that most of the specimens discussed in this portion of the report, series A to G and S, T, and U, failed in fatigue at the geometrical stress raiser at

Fig. 53. Macrographs of Specimens A42, B62, and C7

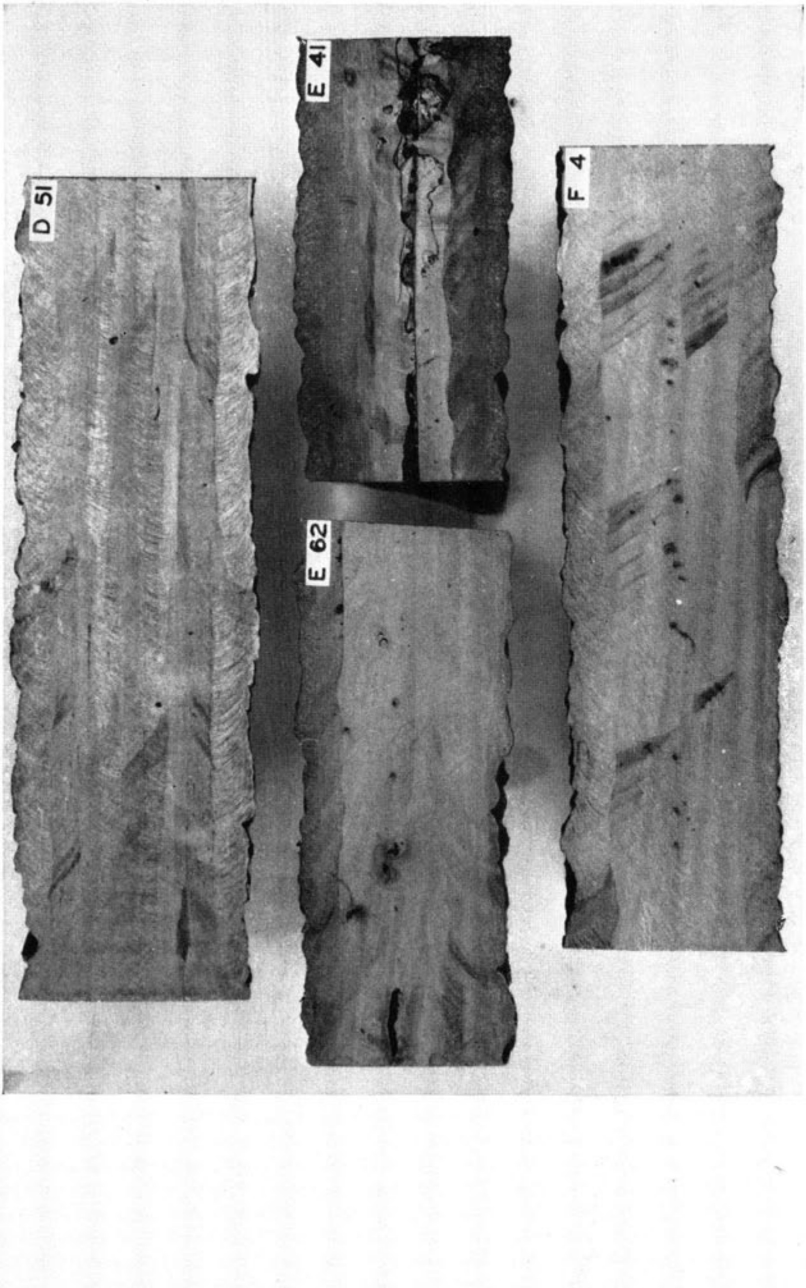


FIG. 54. MACROGRAPHS OF SPECIMENS D51, E62, E41, AND F4

TABLE 32
LOCATION OF FATIGUE FRACTURES; SPECIMENS WELDED IN VARIOUS POSITIONS AND WITH VARIOUS ELECTRODES

Specimen Group	Number of Failures at Edge of Weld	Number of Failures Through Weld	Number of Failures Partly in Weld and Partly at Edge of Weld	Number of Failures in Plate
A	6	...	3	...
B	6	1	2	...
C	7	...	1	1
D	5	2	1	1
E	5	1	2	1
F	3	4	2	...
G	7	...	1	1
S	6	...	3	...
T	5	2	1	1
U	5	1	1	1

the edge of the weld. The F specimens are the only exception. They were predominately weld metal failures.

It is of interest to note that, of the D, E, and F series, the E specimens, which appeared to be most defective in the weld and scarf regions, are represented in Table 32 as having the least number of failures entirely through the weld. In contrast, the F specimens, which appeared to be of better quality than the E specimens, have the largest number of failures entirely through the weld. However, the F specimens had a higher fatigue strength than either the D or E specimens.

17. *Discussion of Results.*—

Specimens Welded in Flat Position

The results of the tests of the X, Y, and Z specimens, summarized in Table 7, and the results of tests of the XX, P, and R specimens, summarized in Table 20, all of which were welded in the flat position, have been included in this study. The results of the tests of the basic series, specimens with a single U groove and welded in the flat position with an E6010 electrode, are reported in column 2 of Table 30. A comparison of each of the commercial series with the basic series was made on the basis of the two relations, ratio of average values and ratio of minimum-to-average values of the fatigue strength.*

A low ratio of average values indicates that the group as a whole had a low fatigue strength. A ratio of minimum-to-average considerably below the ratio of the average values indicates that the specimens of a group were erratic. The smallest value of the minimum-to-average ratio for the basic series was 0.92.

*See footnote, page 21.

Table 33
Fatigue Strength of Commercial Butt Welds; Smallest Ratios of Average Values and of Minimum-to-Average Values
Symmetrical double V grooves welded in flat position with various electrodes

Series	S	T	U	X	XX	P	R
Electrode	E6010	E6020	E6030	E6012	E6012	E6010	E6030
Smallest ratio of average values	0.93	0.94	0.82	0.88	0.89	0.82	0.82
Smallest ratio of minimum-to-average values	0.83	0.89	0.80	0.83	0.85	0.77	0.74

The smallest values of the two ratios for the Y series, the only commercial welds with a single U groove welded in the flat position, were 0.95 and 0.83 for the average and minimum-to-average ratios, respectively. The corresponding values for the specimens with symmetrical double V grooves welded in the flat position are given in Table 33. There were only 9 specimens each for series S, T, and U, and 15 specimens each for the other series. There is a possibility that a larger number of tests of the S, T, and U series would have resulted in smaller minima values, but the low values usually occurred for tests on a cycle in which the stress was reversed, and for which the fatigue strength was based on failure at 2 000 000 cycles. The S, T, and U series each included as many tests of this category as the other series.

The two low ratios of minimum-to-average values are 0.77 and 0.74 for series P and R, welded with E6010 and E6030 electrodes, respectively. The S and U series were welded with E6010 and E6030 electrodes, respectively, and, for these, the ratios of minimum-to-average values were 0.83 and 0.80. It would seem, therefore, that the difference was probably due to the operator rather than to the electrodes. Series S, T, U, X, and XX had no minimum-to-average ratio less than 0.80 but series U had a relatively low ratio of average values, 0.82, for one group, indicating that the fatigue strength of the specimens of this series was consistent but uniformly low. Series T and XX had a combination of high average values and no low individual values, indicating consistent and uniformly high fatigue strengths for these series.

Specimens Welded in Vertical Position

The specimens of series D, E, and F were welded in the vertical position. All had symmetrical double V grooves. The smallest ratios of average values and of minimum-to-average values for each series are given in Table 34. It is of interest to note that both the ratio of

TABLE 34
FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS; SMALLEST RATIOS OF AVERAGE VALUES AND OF MINIMUM-TO-AVERAGE VALUES
Symmetrical double V grooves welded in vertical position with various electrodes

Series	D	E	F
Electrode	E6010	E6012	E6013
Smallest ratio of average values	0.76	0.80	0.94
Smallest ratio of minimum-to-average values	0.70	0.78	0.93

average values and ratio of minimum-to-average values were least for the D series, E6010 electrode, and were the greatest for the F series, E6013 electrode. The specimens of the F series had a consistently high fatigue strength. The specimens of the E series, which had a fair fatigue strength, had a large amount of slag inclusion in the weld, as indicated by the radiographs, the side-bend tests and by the fatigue fractures.

Specimens Welded in Flat Position From One Side and in Overhead Position From Other Side

The A, B, C, and G specimens were welded in the flat position from one side and in the overhead position from the other side. The A, B, and C series had symmetrical double V grooves and the G series had a single U groove. The smallest ratio of average values and of minimum-to-average values for each series is given in Table 35. The B and C series had the most consistently high fatigue strength and the A series the most consistently low fatigue strength.

TABLE 35
FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS; SMALLEST RATIOS OF AVERAGE VALUES AND OF MINIMUM-TO-AVERAGE VALUES
Specimens welded in flat position from one side and overhead position from other side

Series	A*	B*	C*	G†
Electrode	E6010	E6012	E6013	E6030 for U side, E6010 for overhead position
Smallest ratio of average values	0.76	0.89	0.92	0.86
Smallest ratio of minimum-to-average values	0.73	0.82	0.81	0.77

*Symmetrical double V groove.
†Single U groove, U side welded in flat position, other side welded in overhead position.

18. *Summary.*—Because of the erratic character of the fatigue strength of butt welds in plates, no final conclusions can be drawn from the limited number of tests that have been made. Instead, only the general relations between the average and minimum values obtained in these tests will be noted. These relations, as determined from the data in Tables 33, 34, and 35, are as follows:

(1) The specimens welded in the flat position from both sides and those welded in the flat position on one side and in the overhead position from the other side, had approximately the same fatigue strength, as indicated by the ratios of average values and by the ratios of minimum-to-average values given in the following tabulation, only specimens with symmetrical double V grooves being included. The average and minimum values were not quite as great for the specimens welded in the vertical position as they were for those welded in the other two positions. However, one series welded in the vertical position, series F, was as strong as the strongest of the series welded in the flat position.

	Position		
	Flat 8 Series	Vertical 3 Series	Flat on One Side and Overhead on Other Side 3 Series
Average ratio of averages	0.94	0.88	0.93
Average ratio of minimum-to-average	0.88	0.85	0.85
Smallest ratio of minimum-to-average	0.73	0.70	0.73

(2) The values of the fatigue strength of the welds made with various electrodes were as follows:

	Electrode				
	E6010 4 Series	E6012 4 Series	E6013 2 Series	E6020 1 Series	E6030 2 Series
Average ratio of averages	0.89	0.96	0.96	0.97	0.91
Average ratio of minimum-to-average	0.82	0.90	0.92	0.91	0.85
Smallest ratio of minimum-to-average	0.70	0.78	0.81	0.89	0.74

The fact that the values of the fatigue strength, both average and minimum, are highest for the E6013 and E6020 electrodes, should be discounted somewhat by the fact that the tests include only two series welded by the former and only one series welded by the latter. A larger number of tests might have shown some lower values for the fatigue strength of welds made with these electrodes.

(3) It is probable that the difference in the fatigue strength was due as much to the difference in operator skill as to the difference in electrodes, or to the position in which the weld was made.

V. Field Welds
Series M and N; Group 4

19. *Description of Specimens.*—All of the specimens used in the tests described in Chapters II, III, and IV were welded in the shop. The specimens used in the tests described in this chapter were welded in the field. The dimensions of the specimens with field welds were the same as those with shop welds, and the plates were furnished by the Fatigue Committee, and were from the same heat as the plates for the specimens described in Chapters III and IV. Fourteen specimens were welded by each of two contractors. The series were designated as M and N. The plates for all specimens were in the vertical position when the welds were made. Specimens M-V1 to M-V7 and N-V1 to N-V7 were welded as vertical seams; specimens M-H1 to M-H7 and N-H1 to N-H7 were welded as horizontal seams. It was specified that the welds were to be made by qualified welders and were to comply with the other provisions of the A.W.S. 1941 Specifications for Welded Highway and Railway Bridges, but no inspector other than a regular employee of the contractor was provided. Each contractor was allowed to select the electrode and to use his own welding procedure.

All specimens were tested in the as-welded condition.

M Series

The plates for the M series were machined to form a double V butt-weld type of groove, as shown by the broken lines of Fig. 55. The plates were spaced and held in position by tack welding a bar across each end of the welding groove. No tack welds were put in the groove.

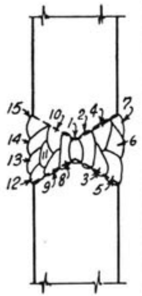
The first pass for the specimens with a horizontal seam was deposited by moving the arc back and forth on a horizontal line, and

(a) Horizontal Seams

Current
Direct
Polarity
Reversed
Preheat
None
Electrode Type
E-6010

Specimen	Atmospheric Conditions	Welded by Operator:
M-H1	46°F., Still, Very Light Rain	1
M-H2	46°F., Still, Very Light Rain	2
M-H3	46°F., Still, Light Rain	3
M-H4	46°F., Still, Light Rain	4
M-H5	30°F., Still	5
M-H6	10°F., Still	6
M-H7	32°F., Still, Clear	7

For M-H1, Typical of All Horizontal Seams



Weld	Layer	Electrode Size	Range of Amperes	Range of Volts	Temperature of Plate Before Depositing Layer
	1	5/32"	120-175	25-30	Atmospheric
	2	3/16"	150-225	30-35	130°F.
	3	3/16"	150-225	30-35	70°
	4	3/16"	150-225	30-35	100°
	5	3/16"	150-225	30-35	120°
	6	3/16"	150-225	30-35	120°
	7	3/16"	150-225	30-35	110°
	8	3/16"	150-225	30-35	120°
	9	3/16"	150-225	30-35	150°
	10	3/16"	150-225	30-35	60°
	11	3/16"	150-225	30-35	140°
	12	3/16"	150-225	30-35	110°
	13	3/16"	150-225	30-35	120°
	14	3/16"	150-225	30-35	130°
	15	3/16"	150-225	30-35	140°

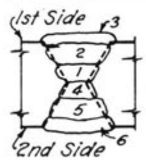
(b) Vertical Seams

Current
Direct
Polarity
Reversed
Preheat
None
Electrode Type
E-6010

Specimen	Atmospheric Conditions	Welded by Operator:
M-V1	40°F., Still, Cloudy	1
M-V2	40°F., Still, Cloudy	2
M-V3	40°F., Still, Cloudy	3
M-V4	40°F., Still, Cloudy	4
M-V5	30°F., Light Breeze, Cloudy	5
M-V6	10°F., Light Breeze, Cloudy	6
M-V7	32°F., Light Breeze, Clear	7

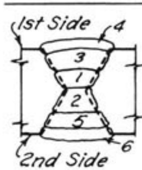
Direction of Welding—Inner Layers Uphill, Outer Layers Downhill.

For M-V1, Typical of M-V2, M-V3 and M-V4



Weld	Layer	Electrode Size	Range of Amperes	Range of Volts	Temperature of Plate Before Depositing Layer
	1	5/32"	120-170	25-30	Atmospheric
	2	5/32"	120-170	25-30	150°F.
	3	3/16"	140-200	30-35	140°
	4	5/32"	120-170	25-30	125°
	5	5/32"	120-170	25-30	210°
	6	3/16"	140-200	30-35	240°

For M-V7, Typical of M-V5 and M-V6



Weld	Layer	Electrode Size	Range of Amperes	Range of Volts	Temperature of Plate Before Depositing Layer
	1	3/16"	150-220	30-35	Atmospheric
	2	3/16"	150-220	30-35	190°F.
	3	3/16"	150-220	30-35	410°
	4	5/32"	120-175	25-30	160°
	5	3/16"	150-220	30-35	220°
	6	3/16"	150-220	30-35	230°

FIG. 55. WELDING PROCEDURE. SERIES M

TABLE 36
WELDING PROCEDURE; FIELD WELDS
N Series. All welds made with E6010 Electrode

Specimen No.	Electrode Size, in.	Number of Passes	Amperes	Volts	Welded by Operator
Horizontal Seams					
N-H1	5/32	8	175	32	A
N-H2	5/32	8	150	30	A
N-H3	5/32	8	175	32	B
N-H4	5/32	10	175	32	C
N-H5	3/16	6	190	52	D
N-H6	3/16	14	190	50	E
N-H7	5/32	13	120	27	F
Vertical Seams					
N-V1	5/32	4	150	30	C
N-V2	3/16	4	180	50	D
N-V3	3/16	12	180	48	E
N-V4	5/32	4	150	30	A
N-V5	5/32	4	175	32	A
N-V6	5/32	4	150	30	B
N-V7	5/32	6	130	25	G

the remaining passes were deposited by moving the arc on a horizontal line in one direction, thus forming stringer beads.

After each pass, the slag was removed by peening lightly with an air hammer and hand-brushing with a wire brush. Any visible defects were chipped out with a round-nosed chisel. The root was chipped to sound metal before welding on the second side. This chipping procedure was done for both the H and the V specimens.

The temperature of the plate adjacent to the groove and midway between the ends was taken with an Alnor Pyrocon Pyrometer before each bead was deposited. The temperatures for specimens M-V1 and M-H1, which are typical for the M-H and M-V specimens, are given in Fig. 55.

The first pass for the specimens with a vertical seam was deposited by moving the arc up and down a vertical line, puddling the metal at the bottom and progressively advancing upward. The remaining uphill and downhill layers of weld metal were deposited by weaving the arc from side to side without back stepping.

Seven operators participated in the welding. Each one welded one vertical and one horizontal seam. One operator welded M-V1 and M-H1, another welded M-V2 and M-H2, etc. All operators used much the same technique but the number of beads used by each varied somewhat.

TABLE 37

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES WELDED IN FIELD; VERTICAL SEAMS

Specimen No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength, F, in 1000's of lb. per sq. in.	Location of Fatigue Cracks*
			$n = 2\ 000\ 000$	
		M Series		
M-V5	0 to +20.0	1009.8	18.3	2
M-V6	0 to +20.0	1356.8	19.0	2
M-V7	0 to +20.0	1161.0	18.6	2
Av.			18.6	
M-V1	+16.0 to −16.0	338.9	12.7	2, 3
M-V2	+16.0 to −16.0	498.7	13.4	2, 3
M-V3	+16.0 to −16.0	1209.5	15.0	2, 3
M-V4	+20.0 to −20.0	142.2	14.2	3
Av.			13.8	
		N Series		
N-V1	0 to +20.0	175.8*†	14.6	1
N-V2	0 to +20.0	215.1	15.0	1
N-V3	0 to +20.0	464.1	16.6	1
Av.			15.4	
N-V4	+16.0 to −16.0	36.1	9.5	1, 2
N-V5	+16.0 to −16.0	59.5	10.1	1
N-V6	+16.0 to −16.0	28.0	9.2	1
N-V7	+16.0 to −16.0	133.0	11.3	1, 2
Av.			10.3	

*See Fig. 4.
†See text and footnote, page 118.

N Series

The plates for the N series were machined to form a double V butt-weld type of groove similar to the groove for the plates of the M series shown in Fig. 55. The welding procedure is given in Table 36. Six operators participated in the welding, each operator welded one horizontal and one vertical seam except operator A, who welded two horizontal and two vertical seams.

20. *Results of Tests.*—The results of the individual tests are shown in Tables 37 and 38 for horizontal and vertical seams, respectively. Since only a few specimens were available, all specimens, except M-V4 and M-H4, were tested on a cycle in which the stress varied from 0 to 20 000 lb. per sq. in. tension, or from 16 000 lb. per sq. in. tension to an equal compression, stress cycles which good welds should have resisted for at least 1 000 000 repetitions. They were planned to give the fatigue strength for failure at 2 000 000 cycles. The fatigue

TABLE 38

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WELDED IN FIELD; HORIZONTAL SEAMS

Specimen No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength, F, in 1000's of lb. per sq. in. $n = 2\ 000\ 000$	Location of Fatigue Cracks*
		M Series		
M-H5	0 to +20.0	1064.8	18.4	2
M-H6	0 to +20.0	1317.6	18.9	2, 3
M-H7	0 to +20.0	1027.8	18.3	2
Av.			18.5	
M-H1	+16.0 to −16.0	405.8	13.0	2
M-H2	+16.0 to −16.0	238.8	12.1	2
M-H3	+16.0 to −16.0	401.9	13.0	2
M-H4	+20.0 to −20.0	148.6	14.3	2, 3
Av.			13.1	
		N Series		
N-H1	0 to +20.0	802.6	17.8	1, 2
N-H2	0 to +20.0	1159.5	18.6	1, 2
N-H3	0 to +20.0	238.7	15.1	1
Av.			17.2	
N-H4	+16.0 to −16.0	113.0	11.1	1, 2
N-H5	+16.0 to −16.0	93.4	10.9	1
N-H6	+16.0 to −16.0	165.3	11.5	2
N-H7	+16.0 to −16.0	357.9	12.8	1, 2
Av.			11.6	

*See Fig. 4.

strength for failure at 2 000 000 cycles was computed from the actual stress and the actual number of cycles for failure by use of the empirical equation $F = S\ (N/n)^{0.13}$. Some specimens failed at a low number of cycles, and the ratio of (N/n) for these differed greatly from unity, and the computed values of $F_{2\ 000\ 000}$ may be seriously in error. However, the stress cycles were the same as those used for the corresponding specimens of the basic series and the relative fatigue strengths can be estimated by inspection from the actual number of cycles for failure.

The results of the tests, given in detail in Tables 37 and 38, are summarized in Table 39. The upper part of the table gives average values and the lower part gives minimum values for each of the several groups of tests. The upper of two lines gives the fatigue strength and the lower line gives the ratio of average values or the ratio of minimum-to-average values for the various groups, as the case may be.

The values given in Table 39 indicate that the specimens welded

TABLE 39

FATIGUE STRENGTH OF COMMERCIAL BUTT WELDS IN 7/8-IN. CARBON-STEEL PLATES WELDED IN FIELD; SUMMARY OF RESULTS

Each average is the average of either 3 or 4 tests and each minimum is the minimum of either 3 or 4 tests.

Stress Cycle	Fatigue Strength, lb. per sq. in. n = 2 000 000				
	Basic Series	Vertical Seams		Horizontal Seams	
		M Series	N Series	M Series	N Series
Average Values					
Zero to tension	22 500 1.00	18 600 0.83	15 400 0.69	18 500 0.82	17 200 0.77
Tension to equal compression	14 400 1.00	13 800 0.96	9 500 0.66	13 100 0.91	11 200 0.78
Minimum Values					
Zero to tension	22 100 0.98	18 300 0.81	14 600 0.65	18 300 0.81	15 100 0.67
Tension to equal compression	13 300 0.92	12 700 0.88	9 200 0.64	12 100 0.84	10 900 0.76

See note at bottom of Table 7, page 21.

in the field by fabricator M were fully as strong as similar commercial butt welds welded in the shop by various fabricators. This statement applies to both the horizontal and the vertical seams.

The specimens of the N series had a very low fatigue strength as indicated by the average and minimum values given in Tables 37 and 38. This was true for both the horizontal and the vertical seams. The specimen N-V1 had a fatigue strength equal to 0.65 of the average fatigue strength of the corresponding group of the basic series.* That specimen N-V1 contained a very poor weld is evident from the character of the fracture shown in Fig. 56. The lack of fusion of the base plate shown in this figure is typical of the fractures of many of the N specimens.

*Unfortunately the exact number of cycles for failure is not known for specimen N-V1. The specimen failed at night when there was no attendant with the machine and the automatic cut-off switch failed to work. In the morning the specimen was broken and the machine was still running. The number of cycles at the evening reading before there were any visible indications of impending failure was 60 000. The number of cycles in the morning was 225 000 and the fracture was battered, indicating that the machine had run some time after failure. The fatigue strength of specimen N-V1 used in Tables 37 and 39 is based on the assumption that failure occurred at 175 800 cycles. If failure occurred at 60 000 cycles, $F_{2\,000\,000}$ would be 12.1 instead of 14.6 as given in Table 37, and if failure occurred at 225 000 cycles, $F_{2\,000\,000}$ would be 15.2. In the former case, the average value of $F_{2\,000\,000}$ for N-V1, N-V2, and N-V3 would have been 14.6, and in the latter case it would have been 15.2, instead of an average value of 15.4, given in Tables 37 and 39. The conclusions to be drawn from the tests would not therefore have been significantly affected if failure for this one specimen had occurred anywhere between 60 000 and 225 000 cycles. If, however, failure had occurred at 60 000 cycles, the smallest value of the ratio of minimum-to-average values for the series would have been reduced from 0.64 to 0.54.

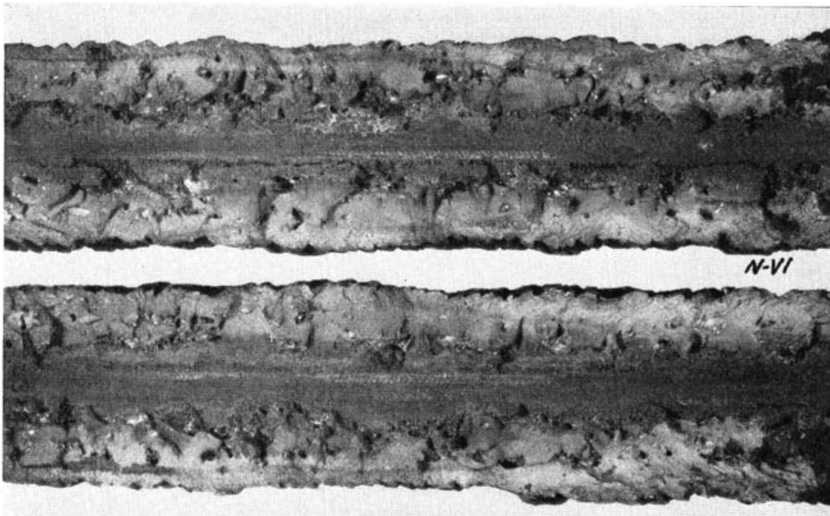


FIG. 56. FATIGUE FRACTURE OF SPECIMEN N-V1

Side-bend test specimens were cut from the part of the weld adjacent to the fatigue specimen, as shown in Fig. 40. Ten of the 12 side-bend specimens of the N series not only failed to pass the test but actually broke. The other two, N-V3 and N-H6, passed the test. Of these two, the fatigue strength was high for N-V3, but only fair for N-H6. Only three M specimens were subjected to the side-bend test, specimens M-V1, M-V2, and M-V4. These were the weakest specimens of the M series welded in the vertical position. The first two passed the side-bend test but the third one was a border-line case.

Static tension specimens of the type shown in Fig. 43 were cut from near the fatigue specimens, as shown in Fig. 40, for 12 of the N fatigue specimens. Two of these failed in the plate and ten failed in the weld. The two that failed in the plate were the two that passed the side-bend test.

The field welds were to have been made in accordance with the American Welding Society's 1941 Specifications for Welded Highway and Railway Bridges. Article 605 (f) of the specifications limits the thickness of a single layer of weld metal to $\frac{1}{8}$ in. except for the throat layer, which may not exceed $\frac{1}{4}$ in. On this basis, it would not be permissible to make a butt weld in $\frac{7}{8}$-in. material in fewer than seven layers.

The report of the fabricator of the N specimens, Table 36, showed

TABLE 40
VICKERS HARDNESS NUMBERS FOR SPECIMENS WELDED IN FIELD

Specimen No.	Temperature deg. F.	Series	Unaffected Base Metal			Heat-Affected Base Metal	Weld Metal		
			Maximum	Minimum	Average	Maximum	Maximum	Minimum	Average
M-H2 Untested		1	152	120	138	224	178	152	166
		2	151	115	130	169	156	141	150
		3	183	131	154	233	177	158	169
									Av. 162
M-H2 after fatigue test	46	1	154	130	140	247	192	151	160
		2	158	122	140	193	179	142	155
		3	(175)	120	140	233	173	154	164
									Av. 160
M-H3	46	1	152	127	140	291	177	150	158
		2	158	122	138	215	181	160	168
		3	146	122	140	246	196	152	164
									Av. 163
M-H5	30	1	158	122	110	301	183	167	172
		2	161	118	138	175	175	168	172
		3	175	127	148	285	199	157	186
									Av. 177
M-H6	10	1	156	120	140	281	180	157	168
		2	155			211	186	176	171
		3	151			235	176	151	162
									Av. 167
M-V3	40	1	142	125	132	210	167	158	162
		2	147	131	140	183	155	135	142
		3	145	128	138	202	176	161	168
									Av. 157
M-V6	10	1	147	129	138	204	167	162	166
		2	145			163	160	152	167
		3	147			204	165	151	161
									Av. 165
N-H4		1	154	120	136	227	208	167	184
		2				172			
		3	160			201	180	160	173
									Av. 179
N-H6		1	157	120	138	199	165	151	159
		2	150			187	148	145	148
		3	144			216	180	158	171
									Av. 166
N-V3		1	139	122	131	176	160	134	146
		2	144			180	153	145	149
		3	142			176	150	138	146
									Av. 147

that, of the 14 specimens, five were welded in 4 layers, two in 6 layers, three in 8 layers, and one each was welded in 10, 12, 13, and 14 layers. Apparently only seven of the welds were made in accordance with the specifications. Of these seven, only one, N-H3, had a fatigue strength less than 0.74 of the average fatigue strength of the corresponding group of the basic series. This ratio is in line with the smallest ratios for the commercial shop-welded specimens welded in the flat position. It was in general the specimens welded in few layers, and in violation of the specifications, that had the lowest fatigue strength. However, the fatigue fracture of many specimens showed a definite lack of fusion at the root that is associated with a low fatigue strength.

As explained in the previous paragraphs, the welding procedure, the lack of penetration at the root of the weld, and the failure of the side-bend and tension static tests to pass the specification requirements, all indicate not only that most of the specimens of the N series did not comply with the specifications, but that the violation of the specifications was so flagrant that it should have been detected by an alert inspector or welding superintendent.

21. *Metallurgical Studies.*—

Hardness Tests

A hardness survey was made on four fatigue specimens of the M-H series, on two each of the M-V and N-H series and on one of the specimens of the N-V series. Hardness tests were also made on an untested portion of the weld taken from a location adjacent to the M-H2 specimen. The location of the indents for series 1, 2, and 3 were the same as for the X, Y, and Z series described in Section 5.

A summary of the hardness values is given in Table 40. The values for the (fatigue) tested and untested M-H2 specimens are given at the top of the table. There was only fair agreement between the two sets of values, the tested specimen having a slightly higher maximum hardness than the untested specimen both in the heat-affected base metal and in the weld metal. Specimens M-H3 and M-H5 had the highest maximum hardness values both in the heat-affected base metal and in the weld metal of any specimen of the M series. This is surprising in view of the fact that the ambient temperature during welding, given in Fig. 55a, was considerably lower for specimen M-H6 than it was for either M-H3 or M-H5.

The M-H6 and M-V6 specimens did not have exceptionally high hardness values in either the heat-affected base metal or in the weld metal even though the ambient temperature during welding was low, 10 deg. F.

The N-H4 and N-H6 specimens were slightly harder in the heat-affected zone than any of the M-V specimens, and the high hardness of 208 Vickers in series 1 of the weld metal of specimen N-H4 is the maximum value for the weld metal in either the M or the N series.

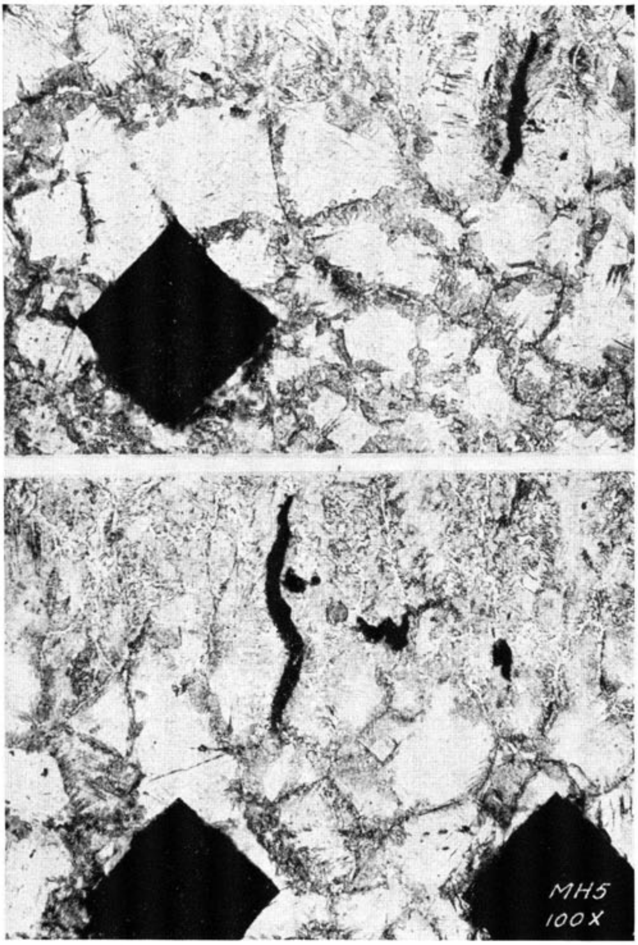


FIG. 57. MICROGRAPH OF SPECIMEN M-H5

Microstructure and Fractures

There was evidence of an acicular microstructure in portions of the heat-affected base metal of specimens M-H3, M-H5, and M-H6 in regions where the hardness values were of the order of 300 Vickers. Two such regions in specimen M-H5 are shown in Fig. 57. The large grains with an acicular core are outlined with fine pearlite of nodular structure. Both micrographs show fissures which bridge the fusion line, and which are believed to have been caused by stresses due to the contraction of the weld. The Vickers indents in these regions

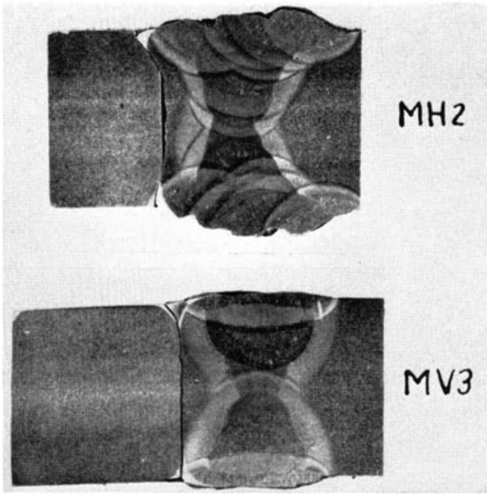


FIG. 58. TYPICAL MACROGRAPHS OF THE M-H AND M-V SPECIMENS

caused cracking along the acicular structure in the grain core, thus indicating a low order of ductility.

The specimens of the M-H series generally exhibited a greater variation in the microstructure and in the hardness of the heat-affected zone and weld metal over the cross sections of the specimen than did the specimens of the M-V series. This difference is attributed mainly to the difference in the welding procedure for the two kinds of welds. This is evident from an inspection of the macrographs of representative specimens, M-H2 and M-V3, of Fig. 58. A number of small stringer beads were used to complete the weld on each side for the M-H2 specimen. The middle bead on each side reheated the bead deposited along the scarf and the previously heat-affected base metal, and the last bead reheated the middle bead but produced a high hardness in the heat-affected base metal. As a result, the M-H welds had an unsymmetrical hardness contour for the series 1 and series 3 surveys, but the M-V welds had the usual symmetrical contour, due to the large size of the final layer on either side of the specimen.

Typical fractures of the N-H and N-V specimens are shown in Fig. 59. The fracture usually started at the root, where there was a lack of fusion, spread into the weld, and emerged at the surface either in the weld area or at the edge of the reinforcement, as shown for N-H2, N-H4, N-V3, and N-V4. Where good root penetration was

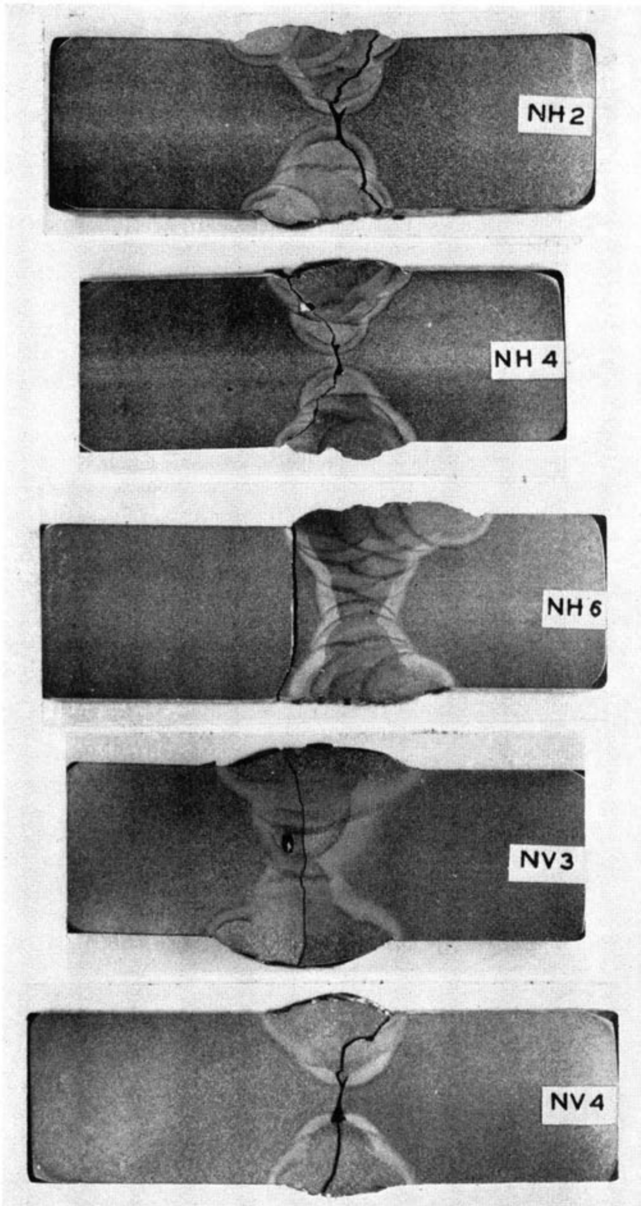


Fig. 59. Typical Fractures of the N-H and N-V Specimens

TABLE 41
LOCATION OF FRACTURES IN SPECIMENS WELDED IN FIELD

Specimen Group	Number of Failures at Edge of Weld	Number of Failures Through Weld	Number of Failures Partly in Weld and Partly at Edge of Weld	Number of Failures in Plate
M-H	7	...	...	...
M-V	6	...	...	1
N-H	1	2	4	...
N-V	...	5	2	...

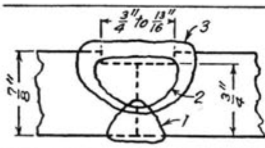
attained, fracture occurred in the base plate, as shown in Fig. 59 for specimen N-H6.

The classification of fractures, given in Table 41, shows that 13 of the 14 M specimens failed at the edge of the reinforcement; the other one failed in the plate away from the weld. Failure at the edge of the reinforcement could be due either to good welds with a high fatigue strength or to a poor reinforcement contour that caused a high stress concentration at the edge of the reinforcement. The values of the fatigue strength, summarized in Table 39, indicates that the former relation prevailed. Only one of the N specimens, N-H6, broke entirely at the edge of the weld. For the others, the fracture was either entirely within the weld or partly in the weld and partly along the edge of the reinforcement. The fractures of practically all N specimens showed a complete lack of fusion at the root, which is an adequate explanation of the low fatigue strength of these specimens.

VI. SPECIMENS WELDED WITH AUTOMATIC WELDERS SERIES K AND L; GROUPS 5 AND 6

22. *Description of Specimens.*—The specimens described in previous chapters were all welded with manually-operated metallic arcs. The specimens used in the tests described in this chapter were welded with automatic welders. Two processes were used, the Carbon-Arc and the Unionmelt. The tests are designated herein as the K and L series, respectively. The dimensions were the same for the automatically-welded as for the manually-welded specimens. The plates were furnished by the Fatigue Committee, and were from the same heat as the plates for the specimens described in the previous chapters.

(a) Welding Procedure

Weld	Pass	Filler Metal	Amperes	Volts	Carbon	Flux
 Tilt 5°, Weld Uphill	1	5/32"	800	38	1/2	220
	2	None	700	40	1/2	220
	3	5/32"	800	38	1/2	220
	Approx Av Joint 790 Amperes, 38 Volts					

(b) Grinding Off Reinforcement

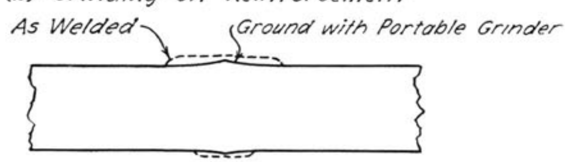


FIG. 60. WELDING PROCEDURE. SERIES K

The welding procedures for the K and L series are given in Figs. 60 and 61, respectively.

All specimens were tested in the as-welded condition except specimens A8, A9, B9, and C2 of the K series. The reinforcement for the latter was ground off so as to eliminate the abrupt change in section at the edge of the weld, as shown in Fig. 60b.

23. *Results of Tests.*—The results of the individual tests are shown in Tables 42 and 43, and a summary of the results is given in Table 44. The fatigue strength for failure at 100 000 and 2 000 000 cycles was computed from the actual stress and actual number of cycles for failure by use of the empirical equation $F = S\ (N/n)^{0.13}$.

For the L series, the average values of the fatigue strength were fairly high, and the tests were fairly consistent, the minimum ratios of average values* and of minimum-to-average values being 0.86 and

*See footnote, page 21.

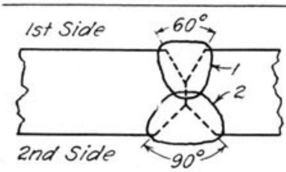
Weld	Pass	Elect Size	Amperes	Volts	Flux
	1 2	3/16" 1/4"	725 750 925-975	30 32	Grade 20, 20X200 Mesh

FIG. 61. WELDING PROCEDURE. SERIES L

TABLE 42
FATIGUE STRENGTH OF AUTOMATICALLY-WELDED BUTT WELDS IN $\frac{7}{8}$-IN. CARBON-STEEL PLATES
K Series

Specimen No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength, F, in 1000's of lb. per sq. in. n = 100 000	Fatigue Strength, F, in 1000's of lb. per sq. in. n = 2 000 000	Location of Fatigue Cracks*
Specimens Tested in As-Welded Condition					
A 1	0 to 25.0	246.1	28.1	....	1, 2
A 2	0 to 25.0	257.2	28.3	....	2
A 7	0 to 25.0	425.5	30.2	....	2
Av.			28.9		
C 7	0 to 20.0	1228.4	....	18.7	2
C 8	0 to 20.0	811.0	....	17.8	2, 3
C 9	0 to 20.0	574.6	....	17.0	1, 2
Av.				17.8	
E 7	+20.0 to −20.0	59.7	18.7	....	2, 3
E 8	+20.0 to −20.0	107.9	20.2	....	2, 3
E 9	+20.0 to −20.0	108.2	20.2	....	2, 3
Av.			19.7		
B 2	+16.0 to −16.0	273.2	....	12.4	2
B 3	+16.0 to −16.0	261.4	....	12.3	2
E 3	+16.0 to −16.0	163.4	....	11.6	2, 3
C 3	+16.0 to −16.0	141.4	....	11.3	1,2
E 1	+16.0 to −16.0	152.5	....	11.5	2, 3
Av.				11.8	
Reinforcement Ground Off (See Fig. 58)					
A 8	+20.0 to −20.0	124.3	20.6	....	2
A 9	+20.0 to −20.0	681.3	25.7	....	4
B 8	+20.0 to −20.0	260.5	22.7	....	1
Av.			23.0		
B 9	+16.0 to −16.0	3303.0†	....	16.0+	...
C 2	+16.0 to −16.0	626.7	....	13.8	1
Av.				14.9+	

*See Fig. 4.
†Did not fail.

0.83, respectively. The corresponding minimum values were 0.79 and 0.76 for the K series. Here, as for other series, the relatively low values were generally for specimens tested for a large number of cycles for failure.

Most of the specimens of the K series had a very abrupt change in section at the edge of the reinforcement, as shown by the broken lines of Fig. 60b. This was a bad stress raiser which extended the full width of the specimen. The edge of the reinforcement was ground off, as shown by the full line of Fig. 60b, for five of the specimens.* The

*Tests of three carbon-arc welds tested in the as-welded condition are reported in Table 5, Bulletin 310. The fatigue strength for these three (0 to tension, n = 2 000 000) were 24 100, 23 300, and 21 000 lb. per sq. in., respectively.

TABLE 43
FATIGUE STRENGTH OF AUTOMATICALLY-WELDED BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES
L Series

Specimen No.	Stress, S, in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Fatigue Strength, F, in 1000's of lb. per sq. in.		Location of Fatigue Cracks*
			n = 100 000	n = 2 000 000	
D 1	0 to 25.0	581.4	31.4	....	1, 2
D 2	0 to 25.0	1330.8	35.0	....	1, 2
D 3	0 to 25.0	563.0	31.3	....	2, 3
Av.			32.6		
D 7	0 to 20.0	2609.9†	....	20.0†	....
D 8	0 to 20.0	1508.6	....	19.3	2
D 9	0 to 20.0	1305.3	....	18.9	2, 3
Av.				19.4†	
G 1	+20.0 to −20.0	245.3	22.5	....	2, 3
G 2	+20.0 to −20.0	104.2	20.1	....	2
B 1	+20.0 to −20.0	261.3	22.7	....	2, 3
G 7	+18.0 to −18.0	1051.3	24.4	16.6	1, 2, 3
G 3	+18.0 to −18.0	306.7	20.8	14.1	2, 3
G 8	+18.0 to −18.0	632.9	22.9	15.5	2, 3
Av.			22.2		
A 3	+16.0 to −16.0	214.1	....	12.0	2, 3
B 7	+16.0 to −16.0	359.9	....	12.8	2, 3
G 9	+16.0 to −16.0	663.0	....	13.9	2
P 15	+16.0 to −16.0	530.0	....	13.5	2
E 2	+15.0 to −15.0	404.4	....	12.2	2, 3
C 1	+15.0 to −15.0	718.9	....	13.1	2, 3
Av.				13.7	

*See Fig. 4.
†Did not fail.

TABLE 44
FATIGUE STRENGTH OF AUTOMATICALLY-WELDED BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES; SUMMARY OF RESULTS

Stress Cycle	Fatigue Strength, lb. per sq. in. n = 100 000			Fatigue Strength, lb. per sq. in. n = 2 000 000		
	Basic Series	K Series	L Series	Basic Series	K Series	L Series
Average Values						
Zero to tension	33 100 1.00	28 900 0.87	32 600 0.99	22 500 1.00	17 800 0.79	19 400 0.86
Tension to equal compression	22 300 1.00	19 700 0.88	22 200 0.99	14 400 1.00	11 800 0.82	13 700 0.95
Minimum Values						
Zero to tension	32 000 0.97	28 100 0.85	31 300 0.95	22 100 0.98	17 000 0.76	18 900 0.84
Tension to equal compression	21 400 0.96	18 700 0.84	20 100 0.90	13 300 0.92	11 300 0.79	12 000 0.83

TABLE 45
VICKERS HARDNESS NUMBERS FOR SPECIMENS WELDED WITH AUTOMATIC PROCESSES

Specimen No.	Series	Unaffected Base Metal			Heat-Affected Base Metal	Weld Metal		
		Maximum	Minimum	Average	Maximum	Maximum	Minimum	Average
Carbon-Arc; K Series								
A7	1	140	127	135	163	149 (165)	128	138
	2	138	126	130	160	153	135	144
B9	1	143	120	132	150	130	123	127
	2	130	124	128	134	133	128	129
Unionmelt; L Series								
D1	1	136	127	132	177	151 (157)	149	150
	2	134	128	130	175	156	147	150
D2	1	141	122	130	174	152 (157)	141	145
	2	144	133	138	167	157 (162)	148	154

elimination of this stress raiser increased the fatigue strength somewhat, as shown by a comparison of the values at the bottom of Table 42 with the values near the middle portion of the same table.

The specimens welded by the automatic processes were neither significantly stronger nor significantly weaker than those welded with a manually-operated metallic arc. The specimens welded with the automatic carbon arc were not quite as strong as those welded with the Unionmelt process, due, it is believed, to the more abrupt change in section at the edge of the reinforcement for the former than for the latter.

24. *Metallurgical Studies.—*

Hardness Tests

Two K specimens welded with the automatic carbon arc and two L specimens welded with the automatic Unionmelt process were surveyed for hardness. The results are given in Table 45. Only two series of readings were taken on each specimen. Series 1 indents were on a line 0.08 in. from the surface of the plate on the side on which the last bead was deposited, the zone of maximum grain size in the heat-affected base metal. Series 2 indents were made on a line that was

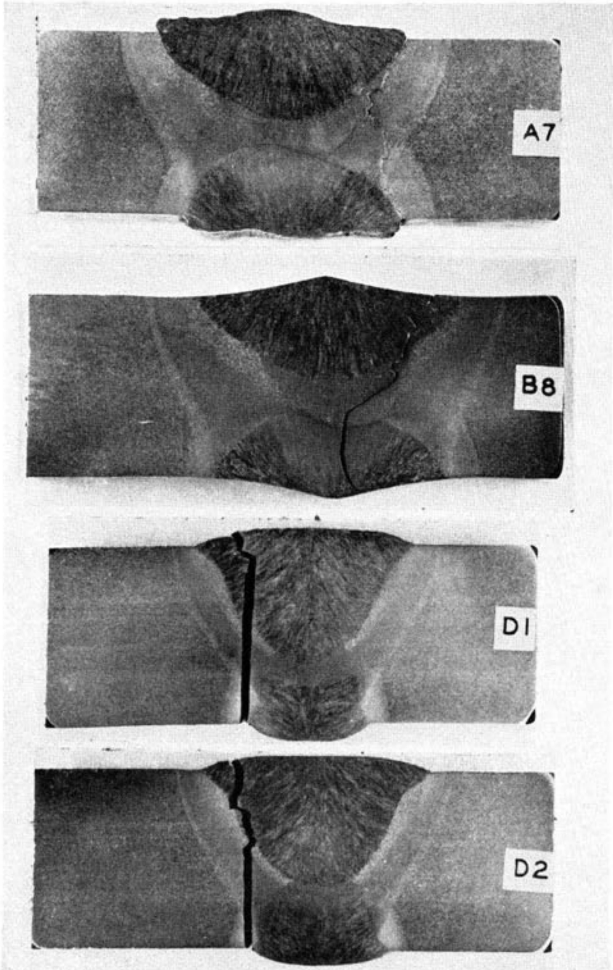


FIG. 62. TYPICAL FATIGUE FRACTURES OF THE K AND L SERIES

0.05 in. from the rolled surface of the plate and transversely across the first bead deposited.

The low hardness of the heat-affected base metal and the large fused area of the weld deposit characterized both the K and the L welds. Hardness values of both heat-affected base metal and weld metal were somewhat lower for the carbon-arc welds than for the Unionmelt welds. The hardness values across the weld metal varied less for the automatic welds than for the manually-welded specimens except where a fracture through the weld had caused some work hardening in the neighborhood of the crack as indicated by the hardness values in the parentheses in Table 45.

Microstructure and Fractures

The columnar structure of the weld metal was more prominent in the automatic welds of the K and L series than in the manual welds. The grains of the prior austenite of the heat-affected base metal were also considerably larger for the automatic welds of the K and L series than for the manually-welded series. The microstructure of the heat-affected base metal of series K and L welds consists entirely of pearlite within the grains which are outlined with thin ferrite boundaries. This structure is consistent with good mechanical properties.

The second bead of the K specimens caused partial recrystallization of the first bead, and the last bead caused complete recrystallization of the second (center) bead, as indicated in the macrograph of specimens A7 and B8, in Fig. 62. The fracture of A7, Fig. 62, is typical of the K specimens tested in the as-welded condition, and the fracture of specimen B8 of Fig. 62 is typical of the fractures of the specimens tested with the reinforcement ground as indicated. The fractures of specimens D1 and D2 of Fig. 62 are typical of the fractures of the L series. The second bead caused approximately 40 per cent of the root deposit to recrystallize.

In general, the welds of the K and L series were without evidence of weld defects such as porosity, unfused areas, or slag inclusions. Practically all of the specimens tested in the as-welded condition failed at the edge of the reinforcement.

VII. T-Butt Welds in ⅞-in. Carbon-Steel Plates Welded With Various Weld Contours

25. *Description of Specimens.*—The specimens described in previous chapters were butt welds in carbon-steel plates, but the specimens of this series had a ⅞-in. transverse plate interposed between the main plates in such a manner as to form a T-butt weld. The specimens of the H series had a T-butt weld with normal reinforcement, while those of the I series had a reinforcement that was ⅛ in. thicker than normal on each side of the weld. The specimens of the J series were identical with those of the H series, but had an additional ¼ in. fillet weld at the junction of the butt plate and the reinforcement. The plates for these specimens were from the same heat as the plates for

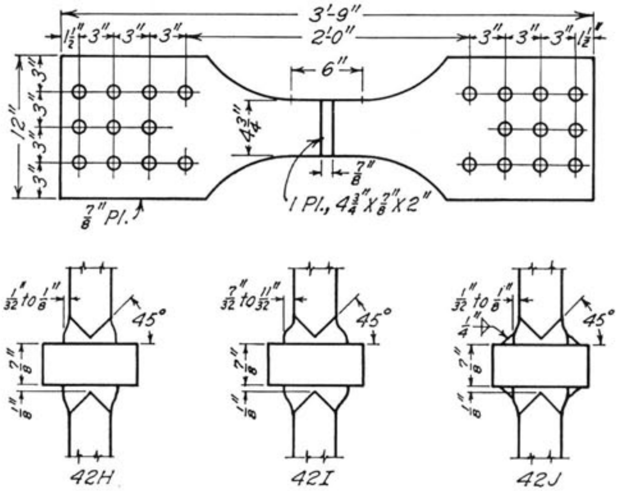
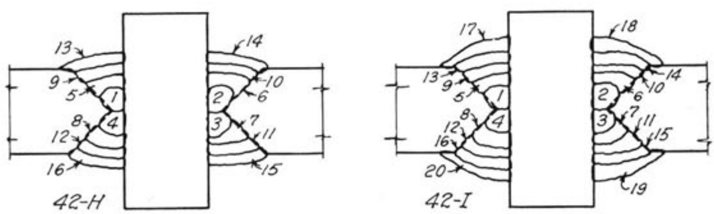
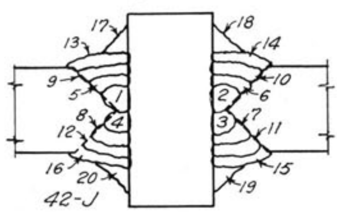


Fig. 63. Details of T-Butt Welds





Root of Passes 1 and 2 back-chipped to sound metal.
Passes lightly peened and wire brushed.

Current-	Direct
Polarity-	Straight
Electrode	E-6012
Position	Flat

Pass	Elect. Size	Amperes	Volts
1 to 4	$\frac{5}{32}$"	275	30
5 to 16 or 20	$\frac{3}{16}$"	310	30

Fig. 64. Welding Procedure for T-Butt Welds

the specimens of groups 3 to 5, inclusive. The details of the specimens and the weld contours are shown in Fig. 63 and the welding procedure is given in Fig. 64.

There were nine specimens in each series. Specimens 1 to 6 were tested in fatigue on a cycle in which the stress varied from zero to tension to produce failure at approximately 100 000 cycles. Specimens 7 to 9 were static test specimens. The T-butt plates of specimens 1 to 3 were cut from ⅞-in. plates, and were so placed that the plane of rolling of the plate was perpendicular to the line of stress. These butt plates were polished and etched to detect laminations but none were found. To avoid the effect of laminations, T-butt plates for specimens 4 to 9 were cut from two-inch plates, and were so placed that the line of stress was parallel to the plane of rolling.

26. *Results of Tests.*—The results of the tests of the three series are given in Table 46. A description of the weld contour and of the T-butt plate precedes each test group. The stress cycle, the number of cycles to failure, and the fatigue strength corresponding to failure at 100 000 cycles are given in the table. Since the tests were essentially comparative, only one stress cycle was used, and the fatigue strength at 100 000 cycles was computed by the empirical equation, $F = S\ (N/n)^K$, using a value of $K = 0.13$. This was the value previously obtained for the butt welds of the basic series. The static strength given is the average of the three specimens 7, 8, and 9 of each series.

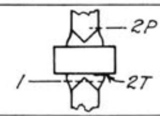
The results of the tests are summarized in Table 47. In the upper half of the table the average values for the groups are given while in the lower half the minimum values are given. The upper line shows the average or minimum fatigue strength of the group and the lower line shows the ratio of either the average or minimum fatigue strength of the group to the fatigue strength of the corresponding basic series.

The tests of this group were fairly consistent, a fact that gives added significance to the rather limited number of tests. The values given in Table 47, the average fatigue strength and the minimum fatigue strength of the T-butt welds, are comparable to those of the commercial butt welds. There was no opening of laminations in the butt plate for any of the specimens and, in most instances, failure occurred either at the junction of the weld metal and the main base plate, or at the junction of the weld metal and the butt plate. For two specimens, 42 H2 and 42 J1, failure was partially in the weld metal.

The ratios of average values for the six specimens of each series were 0.87, 0.83, and 0.83 for the H, I, and J series, respectively; and

TABLE 46

FATIGUE STRENGTH OF T-BUTT WELDS IN CARBON-STEEL PLATES

Spec. No.	Stress Cycles in 1000's of lb. per sq. in.	Number of Cycles for Failure, N, in 1000's	Strength in 1000's of lb. per sq. in.		Location of Fatigue Crack
			Static	Fatigue, F $n = 100\,000$	
1/32" to 1/8" Reinforcement, Plane of Rolling of Butt Plate Transverse to Stress Line					
42H1	0 to +25.0	285.3		28.6	2P 
42H2	0 to +25.0	305.1		28.9	1,2P
42H3	0 to +25.0	557.6		31.3	2P
				Av. 29.6	
1/32" to 1/8" Reinforcement, Plane of Rolling of Butt Plate Parallel to Stress Line					
42H4	0 to +25.0	317.4		29.0	2T (See Diagram Above)
42H5	0 to +25.0	185.8	66.0	27.1	2T
42H6	0 to +25.0	236.1		27.8	2P
				Av. 28.0	
7/32" to 11/32" Reinforcement, Plane of Rolling of Butt Plate Transverse to Stress Line					
42I1	0 to +25.0	228.6		27.8	2P (See Diagram Above)
42I2	0 to +25.0	197.6		27.2	2P
42I3	0 to +25.0	227.8		27.8	2P
				Av. 27.6	
7/32" to 11/32" Reinforcement, Plane of Rolling of Butt Plate Parallel to Stress Line					
42I4	0 to +25.0	264.1		28.4	2P (See Diagram Above)
42I5	0 to +25.0	227.4	69.1	27.8	2P
42I6	0 to +25.0	129.5		25.8	2P
				Av. 27.3	
1/32" to 1/8" Reinforcement Plus 1/4" Fillet, Plane of Rolling of Butt Plate Transverse to Stress Line					
42J1	0 to +25.0	275.4		28.6	1,2T (See Diagram Above)
42J2	0 to +25.0	172.7		26.8	2P
42J3	0 to +25.0	132.9		25.9	2P
				Av. 27.1	
1/32" to 1/8" Reinforcement Plus 1/4" Fillet, Plane of Rolling of Butt Plate Parallel to Stress Line					
42J4	0 to +25.0	310.4		29.0	2P (See Diagram Above)
42J5	0 to +25.0	362.3	68.1	29.6	2P
42J6	0 to +25.0	146.8		26.3	2P
				Av. 27.7	

the smallest ratios of minimum-to-average values were 0.82, 0.78, and 0.78, respectively, for the same series. It appears, therefore, that the additional reinforcement decreased rather than increased the fatigue strength of the T-butt welds.

All static specimens, three for each series, broke in the main plate at a considerable distance from the weld, at a stress appreciably greater than the strength of the control specimens. This increased

TABLE 47

FATIGUE STRENGTH OF T-BUTT WELDS IN ⅞-IN. CARBON-STEEL PLATES WELDED WITH VARIOUS WELD CONTOURS; SUMMARY OF RESULTS

Each value is the average of three tests

Stress Cycle	Single U Butt Weld	Normal Reinforcement		Reinforcement Increased ⅛ in. per side		Normal Reinforcement plus ¼ in. Fillet Welds	
		42 H Series		42 I Series		42 J Series	
	Basic Series	Relation of plane of rolling of butt plate to line of stress					
		Perpendicular	Parallel	Perpendicular	Parallel	Perpendicular	Parallel
Average Values of Fatigue Strength, lb. per sq. in. n = 100 000							
Zero to tension	33 100 1.00	29 600 0.89	28 000 0.85	27 600 0.83	27 300 0.83	27 100 0.82	27 700 0.84
Minimum Values of Fatigue Strength, lb. per sq. in. n = 100 000							
Zero to tension	32 000 0.97	28 600 0.86	27 100 0.82	27 200 0.82	25 800 0.78	25 900 0.78	26 300 0.79

strength is attributed to the short length (relative to the width) that was free to neck. The total length of uniform width at the center was only 6 in. Of this, more than 2 in. at the middle consisted of the butt plate and the adjacent welds, leaving a length of only about 2 inches from the edge of the weld to the point where the specimen began to increase in width, which was free to neck. A portion of the plate adjacent to the weld was probably strengthened by heat treatment. This latter influence was probably slightly less for the H than for the I and J specimens due to the smaller weld deposit. Because this excess strength of the welded specimens over the control specimens appears to be due to a local condition not likely to occur in a structural member, this excess strength is not considered to be significant; and, as a corollary, the excess static strength of the I and J specimens over the H specimens is likewise not considered to be significant.

VIII. SUMMARY

27. *Summary.*—Because of the erratic character of the fatigue strength of butt welds in specimens of the size used in this investigation, the limited number of specimens tested does not justify any final conclusions relative to the fatigue strength of butt welds made

under various conditions. Instead, this summary is limited to the following statements relative to the results of the tests:

(1) The basic series, consisting of butt welds in ⅞-in. carbon-steel plates shop-welded in the flat position with a manually-operated metallic arc and welded under favorable conditions of operator skill and expertness of supervision, gave the average fatigue strengths tabulated below when tested in the as-welded condition.

Stress Cycle	Fatigue Strength in lb. per sq. in.*	
	$n = 100\ 000$	$n = 2\ 000\ 000$
Zero to tension	33 100	22 500
Tension to equal compression	22 300	14 400

*Each value is the average of 3 or more tests.

Tests of specimens that were similar except that they had been stress relieved by heat treatment* showed that the stress relieving had no appreciable effect upon the fatigue strength of the weld.

(2) Tests of six series of commercial butt welds shop-welded in the flat position with a manually-operated metallic arc, welds such as may be expected from a first-class fabricator working under industrial conditions, showed that an occasional weld was appreciably weaker in fatigue than the specimens of the basic series. For series XX, the series for which the fatigue strength was most uniformly high, the smallest ratio of minimum-to-average values was 0.85. This was for specimens tested for failure at 2 000 000 repetitions of a cycle in which the stress varied from tension to an equal compression. The smallest ratio of minimum-to-average values for each of the six series of commercial butt welds were:

Series	X	Y	Z	XX	P	R
Smallest ratio of minimum-to-average values*	0.83	0.83	0.73	0.85	0.77	0.74

*See footnote, page 21.

(3) Tests of commercial butt welds in ⅞-in. carbon-steel plates welded in various positions and with various electrodes are summarized

*"Fatigue Tests of Welded Joints in Structural Steel Plates," Univ. of Ill. Eng. Exp. Sta. Bul. 327, p. 19.

in Table 30, pages 102 and 103. There were some variations in the values of the fatigue strength for the series welded in various positions and with various electrodes, but these variations were probably due to variations in operator skill rather than to differences in electrodes or to the position of welding.

(4) Of the two series of field welds, the specimens of the M series were fully as strong in fatigue as similar commercial butt welds welded in the shop. The N series of field welds, many of which were not made in accordance with the specifications, were seriously deficient in fatigue strength due to a lack of fusion in the base plate at the root of the weld.

(5) The specimens welded by the automatic processes were neither significantly stronger nor significantly weaker than those welded with a manually-operated metallic arc.

(6) The abrupt change in section at the edge of the reinforcement of a butt weld is a serious stress raiser extending across the full width of the specimen, and the fatigue strength of good butt welds in $\frac{7}{8}$-in. plates was increased by a significant amount by grinding or machining the reinforcement flush with the base plate on both sides. The fatigue strength of poor welds is not necessarily increased, and may be decreased, by grinding off the reinforcement.

(7) The most common flaws that caused low fatigue strength in the butt welds, listed in order of importance were: (a) lack of fusion of the base plate, especially at the root of the weld; (b) slag inclusions; (c) blowholes.

(8) The fatigue strength of commercial T-butt welds when tested on a cycle in which the stress varied from zero to tension was not significantly different from the fatigue strength of commercial butt welds in similar plates.

(9) Additional reinforcement above a normal amount decreased rather than increased the fatigue strength of the T-butt welds.

(10) There was no opening of the laminations in the butt plates during these static and fatigue tests of T-butt welds with the plane of rolling of the butt plates perpendicular to the direction of stress. T-butt welds of Type H may be considered as dependable in fatigue as ordinary commercial butt welds, subject to proper assurance against laminations in the interposed butt plate.

This page is intentionally blank.

RECENT PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION†

Circular No. 38. Papers Presented at the Twenty-sixth Annual Conference on Highway Engineering, Held at the University of Illinois, March 1-3, 1939. 1939. *Fifty cents.*

Bulletin No. 313. Tests of Plaster-Model Slabs Subjected to Concentrated Loads, by Nathan M. Newmark and Henry A. Lepper, Jr. 1939. *Sixty cents.*

Bulletin No. 314. Tests of Reinforced Concrete Slabs Subjected to Concentrated Loads, by Frank E. Richart and Ralph W. Kluge. 1939. *Eighty cents.*

Bulletin No. 315. Moments in Simple Span Bridge Slabs with Stiffened Edges, by Vernon P. Jensen. 1939. *One dollar.*

Bulletin No. 316. The Effect of Range of Stress on the Torsional Fatigue Strength of Steel, by James O. Smith. 1939. *Forty-five cents.*

Bulletin No. 317. Fatigue Tests of Connection Angles, by Wilbur M. Wilson and John V. Coombe. 1939. *Thirty-five cents.*

Reprint No. 13. First Progress Report of the Joint Investigation of Continuous Welded Rail, by H. F. Moore. 1939. *Fifteen cents.*

Reprint No. 14. Fifth Progress Report of the Joint Investigation of Fissures in Railroad Rails, by H. F. Moore. 1939. *Fifteen cents.*

Circular No. 39. Papers Presented at the Fifth Short Course in Coal Utilization, Held at the University of Illinois, May 23-25, 1939. 1939. *Fifty cents.*

Reprint No. 15. Stress, Strain, and Structural Damage, by H. F. Moore. 1940. *None available.*

Bulletin No. 318. Investigation of Oil-fired Forced-Air Furnace Systems in the Research Residence, by A. P. Kratz and S. Konzo. 1939. *Ninety cents.*

Bulletin No. 319. Laminar Flow of Sludges in Pipes with Special Reference to Sewage Sludge, by Harold E. Babbitt and David H. Caldwell. 1939. *Sixty-five cents.*

Bulletin No. 320. The Hardenability of Carburizing Steels, by Walter H. Bruckner. 1939. *Seventy cents.*

Bulletin No. 321. Summer Cooling in the Research Residence with a Condensing Unit Operated at Two Capacities, by A. P. Kratz, S. Konzo, M. K. Fahnestock, and E. L. Broderick. 1940. *Seventy cents.*

Circular No. 40. German-English Glossary for Civil Engineering, by A. A. Brielmaier. 1940. *Fifty cents.*

Bulletin No. 322. An Investigation of Rigid Frame Bridges: Part III, Tests of Structural Hinges of Reinforced Concrete, by Ralph W. Kluge. 1940. *Forty cents.*

Circular No. 41. Papers Presented at the Twenty-seventh Annual Conference on Highway Engineering, Held at the University of Illinois, March 6-8, 1940. 1940. *Fifty cents.*

Reprint No. 16. Sixth Progress Report of the Joint Investigation of Fissures in Railroad Rails, by H. F. Moore. 1940. *Fifteen cents.*

Reprint No. 17. Second Progress Report of the Joint Investigation of Continuous Welded Rail, by H. F. Moore, H. R. Thomas, and R. E. Cramer. 1940. *Fifteen cents.*

Reprint No. 18. English Engineering Units and Their Dimensions, by E. W. Comings. 1940. *Fifteen cents.*

Reprint No. 19. Electro-organic Chemical Preparations, Part II, by Sherlock Swann, Jr. 1940. *Thirty cents.*

Reprint No. 20. New Trends in Boiler Feed Water Treatment, by F. G. Straub. 1940. *Fifteen cents.*

Bulletin No. 323. Turbulent Flow of Sludges in Pipes, by H. E. Babbitt and D. H. Caldwell. 1940. *Forty-five cents.*

Bulletin No. 324. The Recovery of Sulphur Dioxide from Dilute Waste Gases by Chemical Regeneration of the Absorbent, by H. F. Johnstone and A. D. Singh. 1940. *One dollar.*

Bulletin No. 325. Photoelectric Sensitization of Alkali Surfaces by Means of Electric Discharges in Water Vapor, by J. T. Tykociner, Jacob Kunz, and L. P. Garner. 1940. *Forty cents.*

†Copies of the complete list of publications can be obtained without charge by addressing the Engineering Experiment Station, Urbana, Ill.

Bulletin No. 326. An Analytical and Experimental Study of the Hydraulic Ram, by W. M. Lansford and W. G. Dugan. 1940. *Seventy cents.*

Bulletin No. 327. Fatigue Tests of Welded Joints in Structural Steel Plates, by W. M. Wilson, W. H. Bruckner, J. V. Coombe, and R. A. Wilde. 1941. *One dollar.*

Bulletin No. 328. A Study of the Plate Factors in the Fractional Distillation of the Ethyl Alcohol-Water System, by D. B. Keyes and L. Byman. 1941. *Seventy cents.*

Bulletin No. 329. A Study of the Collapsing Pressure of Thin-Walled Cylinders, by R. G. Sturm. 1941. *Eighty cents.*

Bulletin No. 330. Heat Transfer to Clouds of Falling Particles, by H. F. Johnstone, R. L. Pigford, and J. H. Chapin. 1941. *Sixty-five cents.*

Bulletin No. 331. Tests of Cylindrical Shells, by W. M. Wilson and E. D. Olson. 1941. *One dollar.*

Reprint No. 21. Seventh Progress Report of the Joint Investigation of Fissures in Railroad Rails, by H. F. Moore. 1941. *Fifteen cents.*

Bulletin No. 332. Analyses of Skew Slabs, by Vernon P. Jensen. 1941. *One dollar.*

Bulletin No. 333. The Suitability of Stabilized Soil for Building Construction, by E. L. Hansen. 1941. *Forty-five cents.*

Circular No. 42. Papers Presented at the Twenty-eighth Annual Conference on Highway Engineering, Held at the University of Illinois, March 5-7, 1941. 1941. *Fifty cents.*

Bulletin No. 334. The Effect of Range of Stress on the Fatigue Strength of Metals, by James O. Smith. 1942. *Fifty-five cents.*

Bulletin No. 335. A Photoelastic Study of Stresses in Gear Tooth Fillets, by Thomas J. Dolan and Edward L. Broghamer. 1942. *Forty-five cents.*

Circular No. 43. Papers Presented at the Sixth Short Course in Coal Utilization, Held at the University of Illinois, May 21-23, 1941. 1942. *Fifty cents.*

Circular No. 44. Combustion Efficiencies as Related to Performance of Domestic Heating Plants, by Alonzo P. Kratz, Seichi Konzo, and Daniel W. Thomson. 1942. *Forty cents.*

Bulletin No. 336. Moments in I-Beam Bridges, by Nathan M. Newmark and Chester P. Siess. 1942. *One dollar.*

Bulletin No. 337. Tests of Riveted and Welded Joints in Low-Alloy Structural Steels, by Wilbur M. Wilson, Walter H. Bruckner and, Thomas H. McCrackin. 1942. *Eighty cents.*

Bulletin No. 338. Influence Charts for Computation of Stresses in Elastic Foundations, by Nathan M. Newmark. 1942. *Thirty-five cents.*

Bulletin No. 339. Properties and Applications of Phase-Shifted Rectified Sine Waves, by J. Tykocinski Tykociner and Louis R. Bloom. 1942. *Sixty cents.*

**Bulletin No. 340.* Loss of Head in Flow of Fluids Through Various Types of One-and-one-half-inch Valves, by Wallace M. Lansford. 1942. *Forty cents.*

**Bulletin No. 341.* Effect of Cold Drawing on Mechanical Properties of Welded Steel Tubing, by Winston E. Black. 1942. *Forty cents.*

Circular No. 45. Simplified Procedure for Selecting Capacities of Duct Systems for Gravity Warm-Air Heating Plants, by Alonzo P. Kratz and Seichi Konzo. 1942. *Fifty-five cents.*

Circular No. 46. Hand-Firing of Bituminous Coal in the Home, by Alonzo P. Kratz, Julian R. Fellows, and John C. Miles. 1942. *Twenty-five cents.*

Circular No. 47. Save Fuel for Victory. 1942. *Twenty-five cents.*

Reprint No. 22. Eighth Progress Report of the Joint Investigation of Fissures in Railroad Rails, by Herbert F. Moore. 1942. *Fifteen cents.*

Reprint No. 23. Numerical Procedure for Computing Deflections, Moments, and Buckling Loads, by Nathan M. Newmark. 1942. *None available.*

**Bulletin No. 342.* Pressure Losses in Registers and Stackheads in Forced Warm-Air Heating, by Alonzo P. Kratz and Seichi Konzo. 1942. *Sixty-five cents.*

**Bulletin No. 343.* Tests of Composite Timber and Concrete Beams, by Frank E. Richart and Clarence B. Williams, Jr. 1943. *Seventy cents.*

**Bulletin No. 344.* Fatigue Tests of Commercial Butt Welds in Structural Steel Plates, by Wilbur M. Wilson, Walter H. Bruckner, Thomas H. McCrackin, Jr., and Howard C. Beede. 1943. *One dollar.*

---

*A limited number of copies of bulletins starred are available for free distribution.

UNIVERSITY OF ILLINOIS

Colleges and Schools at Urbana

COLLEGE OF LIBERAL ARTS AND SCIENCES.—Curriculum in the General Division; general curriculum with majors in the humanities and sciences; specialized curricula in chemistry and chemical engineering; general courses preparatory to the study of law and journalism; pre-professional training in medicine and dentistry.

COLLEGE OF COMMERCE AND BUSINESS ADMINISTRATION.—Fields of concentration in accountancy, banking and finance, commerce and law, commercial teaching, economics, industrial administration, management, marketing, and public affairs.

COLLEGE OF ENGINEERING.—Curricula in agricultural engineering, ceramics, ceramic engineering, chemical engineering, civil engineering, electrical engineering, engineering physics, general engineering, mechanical engineering, metallurgical engineering, mining engineering, and public health engineering.

COLLEGE OF AGRICULTURE.—Curricula in agriculture, dairy technology, floriculture, home economics, and vocational agriculture; pre-professional training in forestry.

COLLEGE OF EDUCATION.—Curricula in education, agricultural education, home economics education, and industrial education. The University High School is the practice school of the College of Education.

COLLEGE OF FINE AND APPLIED ARTS.—Curricula in architecture, art, landscape architecture, music, and music education.

COLLEGE OF LAW.—Professional curricula in law.

SCHOOL OF JOURNALISM.—Editorial, advertising, and publishing curricula.

SCHOOL OF PHYSICAL EDUCATION.—Curricula in physical education for men and for women.

LIBRARY SCHOOL.—Curriculum in library science.

GRADUATE SCHOOL.—Advanced study and research.

Summer Term.—Courses for undergraduate and graduate students.

University Extension Division.—Courses taught by correspondence, extramural courses, science aids service, speech aids service, and visual aids service.

Colleges in Chicago

COLLEGE OF DENTISTRY.—Professional curriculum in dentistry.

COLLEGE OF MEDICINE.—Professional curriculum in medicine.

COLLEGE OF PHARMACY.—Professional curriculum in pharmacy.

University Experiment Stations, and Research and Service Organizations at Urbana

AGRICULTURAL EXPERIMENT STATION
ENGINEERING EXPERIMENT STATION
EXTENSION SERVICE IN AGRICULTURE AND HOME ECONOMICS
BUREAU OF ECONOMIC AND BUSINESS RESEARCH
BUREAU OF COMMUNITY PLANNING
BUREAU OF EDUCATIONAL RESEARCH
BUREAU OF INSTITUTIONAL RESEARCH
PERSONNEL BUREAU
RADIO STATION (WILL)
UNIVERSITY OF ILLINOIS PRESS

State Scientific Surveys and Other Divisions at Urbana

STATE GEOLOGICAL SURVEY
STATE NATURAL HISTORY SURVEY
STATE WATER SURVEY
STATE DIAGNOSTIC LABORATORY (for Animal Pathology)
U. S. SOYBEAN PRODUCTS LABORATORY

For general catalog of the University, special circulars, and other information, address

THE REGISTRAR, UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS